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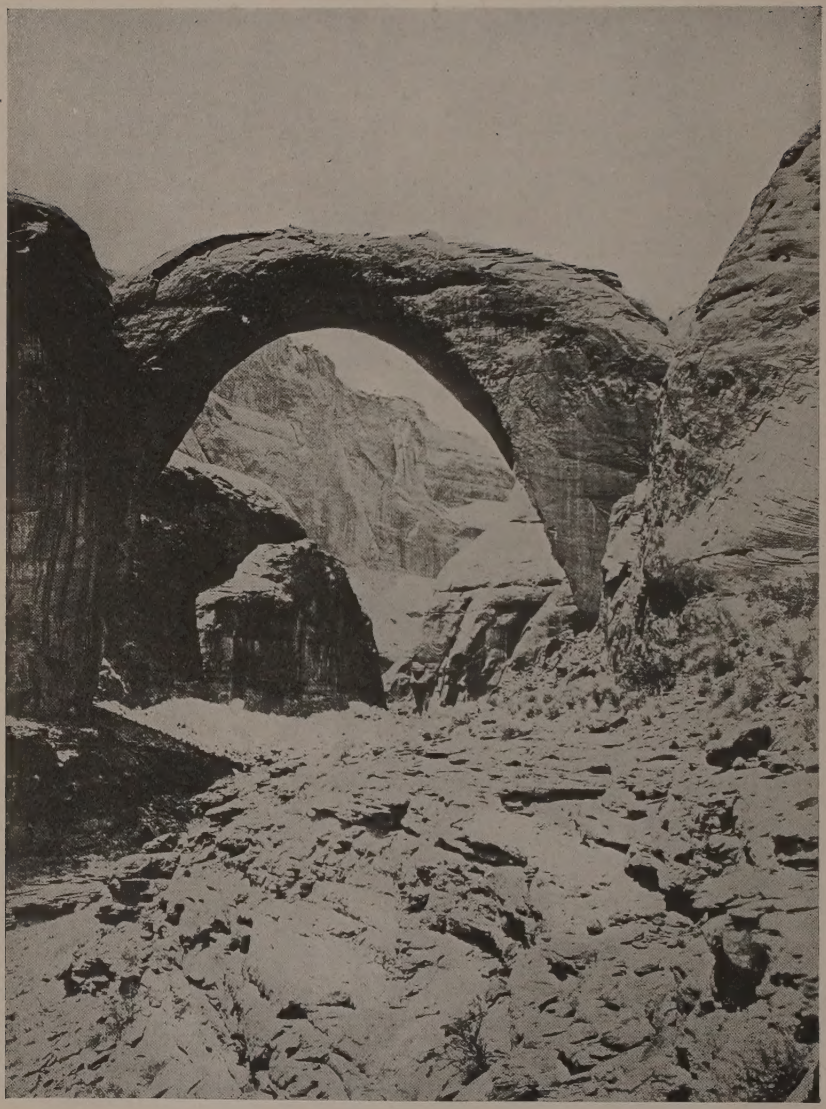

Frontispiece

Barohoini Natural Bridge (Piute for rainbow); northwest of Navajo Mountain, southern Utah. Work of erosion in LaPlata Sandstone. Height 398 feet; width between abutments 278 feet; causeway at top 33 feet wide.

(Photo by H. E. Gregory.)

A TEXT-BOOK OF

GEOLOGY

FOR USE IN
UNIVERSITIES, COLLEGES, SCHOOLS OF SCIENCE, ETC.
AND FOR THE GENERAL READER

PART I

PHYSICAL GEOLOGY

BY

LOUIS V. PIRSSON

PROFESSOR OF PHYSICAL GEOLOGY IN THE SHEFFIELD SCIENTIFIC SCHOOL OF YALE UNIVERSITY

PART II

HISTORICAL GEOLOGY

BY

CHARLES SCHUCHERT

PROFESSOR OF PALEONTOLOGY IN YALE UNIVERSITY AND OF HISTORICAL GEOLOGY IN THE SHEFFIELD SCIENTIFIC SCHOOL

NEW YORK
JOHN WILEY & SONS, INC.
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1915

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LOUIS V. PIRSSON AND CHARLES SCHUCHERT

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BOSTON, U.S.A.

Dedicated to the Memory

OF

JAMES DWIGHT DANA

EXPLORER, GEOLOGIST, NATURALIST,

PROFESSOR IN YALE UNIVERSITY

PREFACE TO PART I

For many years the author of this book has been called upon to give the first course in Physical Geology to large classes of students, among whom are to be found those pursuing courses leading to professional work in various branches of Engineering, Mining, Metallurgy, Forestry, Chemistry, etc., and in Geology itself, to whom therefore the subject has a direct technical value or serves as a basis for further technical studies. Naturally these students find a first general course in Physical Geology one of cultural interest as well.

In the pursuit of this work the writer has long felt the need of a textbook which, while presenting the broad facts and principles of the science from the latest viewpoint, should have a character somewhat different, and a balance more even in the subject matter composing it, than is to be found in available texts. Undoubtedly the majority of students who follow the first course in Geology in the colleges and higher schools do so primarily for its cultural aspects; less often for its technical interest. As a sequence of this it commonly happens that the science is presented to them largely from the physiographic side, both because this method of approach demands less background in preparation by previous basal studies, and because it concerns those aspects of the subject which are of more general popular interest and apprehension. Some recent textbooks are indeed treatises on physiography under another name. In this work the attempt has been made to preserve a more even balance and while giving this part of the geologic field its due share of attention, to also give weight to the structural one, and to the physical and chemical sides of the subject as well. While the work has thus been written to supply the author's wants, it is hoped that it may prove useful to other teachers of the science who may have felt a similar need.

Although original matter or views of problems have been incorporated in places, it is obvious that the preparation of a work of this nature must mainly be one of selection of the subject matter from published material. It would be impossible to give the greatly varied sources from which it has been drawn, but it may be mentioned that the general treatises of Dana, Geikie, Chamberlain and

Salisbury, Haug, Suess, and others, together with the wealth of material embodied in the reports and bulletins of the United States Geological Survey, have been freely used, as well as other works in special fields too numerous to mention.

For efficient help, freely given, in the reading and preparation of different parts of the text, the author wishes to render grateful acknowledgment to his friends and colleagues, Professors J. P. Iddings, J. D. Irving, W. E. Ford, and especially to Professor Joseph Barrell whose criticism and advice were of the greatest service.

In the matter of illustrations the writer desires to express his obligations especially to Dr. George Otis Smith, Director of the United States Geological Survey, who placed at his disposal its great mass of photographic material; the proper credit for these photographs being given in each case; to Mr. J. J. H. Teall, recent Director of the Geological Survey of Great Britain; to Professor G. P. Merrill of Washington, D. C.; to Professor J. E. Talmage of Salt Lake City; to Mr. G. W. Grabham of Khartoum, and to many other friends whose names are credited in each case.

L. V. PIRSSON.

Sheffield Scientific School of Yale University,
New Haven, Conn.,
Dec., 1914.

PREFACE TO PART II

During the past ten years the writer has been giving a course in Historical Geology to undergraduate students in the Sheffield Scientific School of Yale University. From crude beginnings these lectures have gradually evolved into those here presented. At first they were based on Le Conte's widely known *Elements of Geology*, but as the writer's experience in teaching grew, he was led more and more away from that book. As the course developed, it was found desirable to introduce lectures showing the relationship of Historical Geology to Astronomy and Evolution, Biology and Oceanography, such as are given in Chapters XVII to XXVI. In addition it became apparent that most American students taking the first year's work in Geology, even those intending to devote their lives to the earth sciences, are often deficient in the elements of Botany and Zoölogy, and the existence of this unfortunate condition made it necessary for the writer to include also some discussion of the living world. As a result of this, the course became harder, but it gained in interest because of its wider scope, and, after all, Historical Geology is as much a biological science as it is a geological.

The material upon which the lectures are based has naturally been drawn from so many sources and has become so integral a part of the writer's fund of information that it is not easy to render complete acknowledgment. The well-known general treatises and works of Dana, Suess, Le Conte, Chamberlin and Salisbury, Scott, Geikie, Kayser, Walther, Neumayr, Credner, Jukes-Brown, and Lapparent are of course the main sources. Of great service have also been the more general works on paleontology of Zittel-Eastman, Osborn, Scott, and Williston; the zoölogies of Thomson, Parker and Haswell, and Weysse; the works on man by Sollas, Keith, and Huxley; the histories of Zittel, Geikie, and Merrill; the treatises on oceanography by Krümmel, Murray and Hjört, and Johnstone; astronomy as presented by Hale and Arrhenius; Clarke's work on geochemistry; and, for stratigraphy, Willis' great and comprehensive *Index*. Finally the wealth of fact and illustration in the works of the United States Geological Survey has been drawn upon freely.

The writer is much indebted to Doctor George Otis Smith, Director of the United States Geological Survey, and to Doctor Bailey Willis

for the great help given him in the preparation of the geological map of North America, which first appeared in Bowman's *Forest Physiography*. Other information and illustrations have been taken from the guides of the British Museum (Natural History), Koken's Führer to the University of Tübingen Museum, Fraas' Führer to the Stuttgart Museum, the state surveys of New York, Maryland, Ohio, Indiana, Minnesota, and New Jersey, and from other sources mentioned in the text and in the figure legends. Acknowledgment is due the Macmillan Company for permission to reproduce a number of illustrations from Osborn's *The Age of Mammals* and Scott's *A History of Land Mammals in the Western Hemisphere*, and the courtesy of the two authors in granting this privilege is also much appreciated.

The writer is grateful to his colleagues Professor Joseph Barrell for contributing Chapter XXV and several smaller sections and for reading and criticizing fourteen chapters, Professor Richard Swann Lull for allowing him to reprint Chapter XLVI, which first appeared in the *Yale Review*, and for aid in nine other chapters, and Professor Herbert E. Gregory for photographs. Thanks are also extended to his friends Doctor T. W. Stanton for aid on the Mesozoic chapters, Doctor George Grant MacCurdy for reading the one on man, Doctor John M. Clarke for help on the Devonian chapter and for photographs, and Doctor E. O. Ulrich for preparing the statement of the Ozarkian.

To Miss Clara Mae LeVene the author is especially thankful for the untiring editorial revision she has given the manuscript, and for seeing the book through the press.

The pen drawings have been made by Mr. William Baake and Doctor Stanley C. Ball.

CHARLES SCHUCHERT.

Peabody Museum of Yale University,
New Haven, Conn.,
July, 1915.

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PART I

PHYSICAL GEOLOGY

BY

L. V. PIRSSON

TEXT-BOOK OF GEOLOGY

INTRODUCTION

GEOLOGY AS A SCIENCE, AND ITS SUB-DIVISIONS

Geology is that branch of Science which treats of the Earth, comprehensively, as a subject of research and study. It seeks to explain the origin of the earth, especially in its relations to other planets, and to the Solar System of which it is a part; it endeavors to account for its varied surface features, for its atmosphere, the distribution of land and water, its rivers, lakes and seas, its mountains and plains. It studies these features in the light of varied forces and agencies operating upon them, and attempts to show their history during long ages past. It takes account of the materials composing the earth, and, from the remains of plants and animals still existing in the rocks, it aims to present a picture of the successions of living organisms which have existed during past times down to the present.

Geology is essentially an historical science in that it continually seeks to determine the origin of things and the changes which they have experienced. The documents upon which the history is based are written in the rocks of the earth itself and the forms of its surface features; they present a series of incontrovertible records, and, if we would read this history, it is our part to learn to decipher the records correctly. Much of this has been done, but much also remains to be done; it is the aim of this work to present a general account of what has been accomplished. Many writers define Geology as a history of the earth and its inhabitants, as shown by the record in the rocks.

Geological Sciences. — From what has been stated above it is clear that the material treated in Geology is of wide extent, and embraces a great variety of subjects. Hence, with the development of the science, the increasing fund of information gained has become so extensive that different branches of Geology, or geological sciences, have come to be generally recognized as separate

fields for research and study. Some of the more important of these are as follows:

Mineralogy, which deals with the origin, composition, and properties of inorganic chemical compounds, which exist already formed in the earth's crust.

Petrology, which treats of the origin, properties, and relations of the material forming the various rock masses which are component parts of the earth's crust.

Meteorology, the science of the earth's atmosphere and its various phenomena, such as variations of heat and cold, of its moisture, and its movements, as seen in winds and storms.

Paleontology, the science which deals with the life of past ages, as shown by the remains or natural molds and imprints of plants and animals, called fossils, which have been preserved, enclosed in the rocks.

Physiography, the science which treats of the present surface of the earth and seeks to understand the causes of its relief features and the nature of the various agencies which are at work modifying them. It might indeed be called the geology of the present.

Economic Geology, which deals chiefly with the use of the materials of the earth's surface in the service of mankind, and in the application of geological facts and principles in obtaining them.

While the recognition of these branches of science, which have developed from the main stem of Geology as separate lines of inquiry and study, has narrowed that of Geology proper, so called, it must yet be understood that they are really special phases of the subject, intimately related to it, and that some knowledge of them is necessary for a proper comprehension of Geology in its broader aspects.

Sub-divisions of Geology. — Very briefly stated, Geology may be considered thus. A mass of varied materials has been, and is being, acted upon by certain agencies, by which definite results have been, and are continuing to be, produced. We may study and determine the nature of the materials operated upon; we may consider the kinds and modes of operation of the agents and forces; and, lastly, we may learn the character and extent of the results achieved. From this it naturally follows that there are three main sub-divisions of Geology, as follows:

Dynamical Geology, a consideration of the facts and principles concerning the various dynamical agents, such as wind, running water, moving ice, volcanic activities, etc., which operate upon the earth, and modify its outer portion.

Structural Geology, an account of the nature, properties, relations and positions of the component rock masses of the outer part of the earth. It includes the architecture of the outer shell of the earth. These two, dynamical and structural geology, as opposed to historical geology, may be classed together under the general heading of *Physical Geology*.

Historical Geology, a review of the sequence of the events which have happened to the earth in the past, as revealed by the rocks and fossils. This includes *Paleogeography*, or the varied dispositions of land and sea and their character in former ages, and *Paleontology*, which has been mentioned above as picturing the different successions of organic life which have inhabited the earth.

It is clearly evident that a knowledge of structural and dynamical geology is requisite for a proper understanding of the historical portion of the subject and must therefore precede this. From the purely philosophic side it would seem natural to inquire into the character of the masses operated upon before engaging in the study of the forces modifying them, but it is impossible to treat structural geology without some reference to dynamical geology; to consider results without considering causes. Moreover, the various agencies which have worked in the past are at work now, and their operations are in some degree familiar to all. By thus treating dynamical geology first the mind is led from the known to the unknown, and from the present to the past. It therefore appears more logical for the beginner to study dynamical geology first, even though this may cause some repetition in succeeding phases of the subject, and this order has therefore been adopted in this work.

Method of Geological Study. — In former times it was thought that the more prominent and striking features which relieve the earth's surface were due to some sudden and violent action. Thus in surveying a deep canyon, or gorge, scoring the earth's surface, or a towering rock mass giving rise to a mountain peak or tall cliff, it was customary to say that this must have been "caused by some great convulsion of Nature" and this idea with its phrase still persists, and is frequently used by those untrained in geology. It is often seen in descriptions of natural scenery. A great convulsion of nature is a *cataclysm*, and it was thought that the varied changes which the earth's surface has evidently undergone were due to a series of cataclysms, produced by some sort of unknown and terrible forces. The error in this method of thinking is that the element *time* is not taken into account. A given result may be equally achieved by a great force acting very quickly, or by a small force acting through a long period of time. It is the triumph of Geology, as a science, to have demonstrated that we do not need to refer to vast, unknown, and terrible causes the relief features of the earth,

but that the known agencies at work today are competent to produce them, *provided they have enough time.* Thus, we know, for reasons we shall see later on, that the gorge seen in the accompanying illus-

Fig. 1. — Grand Canyon of the Yellowstone River.

tration, Fig. 1, has been cut into the earth's surface by the scratching of the sand and gravel dragged along by the river during the lapse of a vast length of time. Therefore the method of geological

research may be defined as *an inquiry into the past in the light of the present*, of the solving of the unknown by the application of the known.

Geologic Time. — The recognition of the element of time has been stated above as of fundamental importance in geological reasoning. Yet this generally involves a new conception to one beginning the study of the science. As in taking up the study of Astronomy one has to gain new ideas of distance, and to think no longer on a basis of feet, yards, and single miles, but in terms of millions of miles, so in Geology one is compelled to think in vast lapses of time, which in many cases are to be measured in millions of years. Since we have no accurate measures of time in Geology, as we have of distance in Astronomy, the phrase "speaking geologically" is often used with "great" or "small," "long" or "short" to indicate relative lapses of what, from the human standpoint, may be enormous periods of time. Thus, speaking geologically, a million years may be relatively a short interval.

Basal Sciences. — A subject so comprehensive as Geology is largely based upon and has close relations with other sciences. The most fundamental of these are Chemistry and Physics, some knowledge of which is essential. Some acquaintance with Mineralogy is also highly desirable, though in a measure the want of this may be supplied during the consideration of the subjects to which it applies. On the cosmical side Geology passes into Astronomy, and in the study of Paleontology familiarity with the elements of Zoology and Botany is needed. Other subjects, such as Geography and Mathematics, might be mentioned, but it is assumed that the student has already acquired as much of these as is needed.

DIVISION I. — DYNAMICAL GEOLOGY

CHAPTER I

GENERAL CONSIDERATIONS; THE ATMOSPHERE AND ITS WORK

Dynamical geology is a consideration of the facts and principles relating to the different agencies which are now modifying the surface of the earth. They may be broadly divided into two main groups; *external* — those whose controlling energy is derived from sources exterior to the earth, chiefly from the sun and in lesser degree from the moon; and *internal* — those whose operations appear to be due mainly to the interior heat and to the gravitative force of the earth. They may be classified as follows:

External Agencies	Internal Agencies
The Atmosphere.	Underground Water.
Rainfall and Streams.	Volcanoes.
Lakes.	Earthquakes.
The Ocean.	Slow Movements of the Earth's Crust.
Snow and Ice.	
Organic Life.	

Rate of Work. — When it came to be appreciated that these known agencies were sufficient to have produced the present relief features of the earth, and the varied structures of its outer shell, as investigation has revealed them, in a natural reaction from the previous ideas that these were due to successive cataclysms, a view arose that these agencies had always worked with great uniformity, at the same rate and with the same intensity that they do today. This view is no longer held, as it appears that in some periods in the past the action of some of them has been more intensive than in other periods, and it seems probable that, while on the whole the energy has been declining, that of some has been gradually increasing. The reasons for thinking this will appear in the course of this work, as the different subjects are taken up.

The actual rate at which geological work is accomplished, from the human standpoint, is, in general, very slow. Of course in some cases, as where in a volcanic eruption, a very large amount of matter

is suddenly transferred from the inside to the outside of the earth, the work done is not only evident, but startling. The same would be true for instance in the case of heavy landslides. But, in general, the amount of work done at this rate is small, compared with that accomplished, much of it imperceptibly, most of it so slowly, that it is only in viewing the results achieved that we can truly judge of its extent. As in looking at the hour hand of a clock we see no perceptible movement at a given instant and yet know by comparison the movement is taking place, so we infer that many geological processes have been very slowly, but none the less steadily and ceaselessly occurring. It is the recognition of this that forces us to acknowledge the lapse of immensely long periods of time, as previously stated in the introduction.

The Atmosphere and its Work

Character and Composition. — The atmosphere is the outer gaseous envelope of the earth. Owing to the compressibility of gases it is densest at sea-level, where it exerts an average pressure of nearly 15 pounds to the square inch. It regularly decreases in density as one ascends, but its height is not known; however, since meteors passing through space, on coming in contact with it, become heated and luminous, and exhibit this phenomenon at least 100 miles above the earth, it certainly extends upward to this point in appreciable quantity and in more diffuse form to considerably

Fig. 2. — Diagram showing a segment of the earth with the atmosphere 50 miles high in true proportion.

greater heights. At 50 miles it is extremely rare, and at about 3.6 miles (19,000 feet) its density is only one half that at sea-level, that is to say one half of the actual amount of air lies below this level.

In composition the air consists of about four parts of nitrogen to one of oxygen. While these are the chief elements there are also carbonic acid gas, CO_2, in the proportion of about 3 volumes in 10,000 of air, and water vapor whose quantity varies according to temperature, locality, and season; under ordinary conditions in our living rooms a cubic yard of air carries from 1/5 to 2/5 of an ounce of water, or from about one to two tablespoonfuls. In addition there are relatively minute amounts of other gases and volatile

compounds in the air, but these are not of geological importance, and may be disregarded in this connection.

Origin of the Atmosphere. — A discussion of the origin of the atmosphere must in some measure involve that of the earth itself, and while it is inadvisable to consider the latter until later, when the student is better prepared for it, the following considerations are of interest in this connection. Of the different views which have been held regarding the atmosphere's origin no one has, as yet, received recognition as fully satisfactory. They may be roughly classed into two groups. According to the first, the origin of the atmosphere dates back to that of the earth. It is held that the matter composing the earth was once a great mass of extended, heated gas and vapor, part of a larger mass which formed the solar system. As this cooled and contracted it eventually produced our solid earth, but the part which still remained gaseous now forms our atmosphere. Thus the latter is thought to be coeval with the earth.

According to the other view the earth had originally little or no atmosphere; the gases which compose it being held occluded, that is absorbed, in its mass, and as the earth has contracted, either through cooling and crystallizing or through gravitative force, they have been excluded, squeezed out, and now form the atmosphere. This view, in part, might be illustrated by the action of silver which, when melted, absorbs oxygen from the air and holds it occluded; when it solidifies the gas is again returned to the air with explosive violence.

Following the first view the atmosphere, especially its content in carbon dioxide, has been gradually diminishing in amount; following the second it has been gradually supplied. Various modifications of these views, especially endeavoring to account for variations in the amount of oxygen, water vapor, and carbon dioxide, which are the substances chiefly important as agents in geological processes, have been suggested. Thus for example it has been held, since vegetable life takes carbon dioxide from the atmosphere and decomposes it, storing up carbon and liberating oxygen, that originally the atmosphere was full of carbon dioxide and deficient, or wanting, in oxygen, but that through this action of plants the conditions have been gradually reversed. The student should, however, remember that these views are hypothetical, and that science is not yet able to pronounce authoritatively upon them. Where they concern the aspect of special questions they will be considered in detail in their appropriate places.

Importance of the Atmosphere. — The atmosphere is an agent of the highest importance in surface geological processes. Not only does it work directly in both a destructive and a constructive way, but without it there could be no work from rainfall and running water, as we now know it, and the activities of plant and animal life would cease. Water, without at least an atmosphere of water vapor above it, could not remain on the surface of the globe, which would then be dead and inert, and surface changes, due to external agencies, would not occur. This is illustrated by the moon, which appears to have no atmosphere or water upon it, due apparently to the fact that its mass is not great enough to exert sufficient force of gravity to retain around it the gases which might have formed its atmosphere. Its surface features, as revealed by the

most powerful telescopes, seem to be those produced by internal agencies, largely volcanic in nature, and by the impact of meteoric bodies from space, unmodified by later changes due to atmospheric effects.

Work of the Atmosphere. — It has been stated above that the work of the atmosphere may be regarded as both destructive and constructive. The former consists in its *chemical* action upon rocks and minerals, whereby former chemical compounds are broken up and new ones formed in their places, and in its *mechanical* activity by which material driven by the wind is not only transported but abrades and wears away exposed rock surfaces. Its chemical action is so greatly aided by water coming in the form of rain and by the expansive power of frost that it is difficult to separate these agencies and they will consequently be considered later under the general term of *weathering*. The constructive work is performed by the wind, which is a factor of considerable importance in transporting and depositing material. This classification may be shown in a table as follows:

Work of the Atmosphere

Destructive	Chemical, Decay of Rocks (Weathering).
	Mechanical, Wearing of Rocks (Wind-driven Sand and Waves).
Constructive, Transport and Deposit, Formation of Dunes, Loess, etc.	

Destructive Work. — Omitting for the present the work of weathering and of the waves, which are better considered in connection with that of water, the destructive effects of the atmosphere as a geological agent are best seen in those places where sand driven by the wind wears away exposed rock surfaces. In humid regions, where the rainfall promotes the growth of abundant vegetation, the soil is protected, the wind is unable to lift and carry it, and thus having no tool to work with, its abrasive effects are negligible, or wanting. Moreover, in such regions exposed rock surfaces are less conspicuous, and are apt to be covered by a mat of plant life which serves as a cushion to protect them. In arid regions on the contrary, where there is little or no rainfall, vegetation is scanty or lacking and the loose soil is constantly being shifted by the wind and driven against the exposed rock-masses. This is, of course, most strikingly seen in deserts. In such places rocks or boulders outcropping from the soil are worn and polished by the sand constantly drifting past and over them. In dry canyons in arid countries, as in the southwest part of the United States, the rocky walls are carved and smoothed, and the lower part undercut into caves by

the sand-drift. The constant pounding of the sand grains wears away the softer parts of the rocks leaving the harder ones projecting, often in intricate fret-work. If the wind has a prevailing direction, the harder and softer parts are often worn into parallel groovings. The wind also helps in the general process of rock decay by carrying material away, and thus exposing fresh surfaces to the attack of both wind and weather. The efficiency of the wind as a

Fig. 3. — Looking Glass Rock, near La Sal Mts., Utah. White horse near tree gives scale. Cut and worn to its present shape, largely by wind erosion. W. Cross, U. S. Geol. Surv.

factor in the wearing away of land surfaces and transporting material in arid regions has probably been underrated; some would attribute to it the formation of the more prominent features of relief of the land in such countries.

The *rate* at which such work is carried on is faster than would at first be imagined. We may gain some idea of it from the fact that the window glass of houses along sea-shores, which are directly exposed to storm-driven sand, may lose their transparency in a day or two and be completely penetrated in a month or so. It was the observation of this that led to the use of the artificial sand-blast as an instrument for the etching of glass and stone. Telegraph poles planted in the desert are quickly cut down by the sand drifting past their bases.

Constructive Work. — This is illustrated in the deposits formed by the wind from transported material. A gentle breeze lifts and carries dust, a strong wind drives sand along with it, while a tempest may move gravel the size of peas and transport vast quantities of material; see Fig. 4. Under favorable conditions the material thus transported, and dropped as the wind slackens, may form deposits which are sometimes of great magnitude. They are known

Fig. 4. — Sand-storm sweeping over Khartoum North; in front is the Blue Nile. Shows enormous transporting power of the wind. Soudan, June 6, 1906. (Photo. by Wm. Beam, M.D.)

as *eolian* (Æolus, god of the winds) deposits, a term used to distinguish them from sedimentary deposits formed in water. They are most prominently illustrated in dunes and in the loess.

Dunes. — Sand-hills, or dunes, are hillocks, or hills, made by wind-borne sand in a manner similar to that in which snow forms drifts. They vary in height from a few feet up to 100, or even 200, feet or more. The sand grains composing them are mainly of quartz,* though a variety of other minerals may occur, rounded by the rolling and abrading action they have undergone. The starting of a dune may have been caused by some obstacle, such as a stump or stone, causing a temporary lull in the wind behind it. Sand is here deposited and the dune, once begun, continues to grow. In regions where they occur the erection of buildings has in this way started

* If the student is not acquainted with the ordinary rock-minerals he may gain such acquaintance with them as is necessary in the study of this work by referring to Appendix A.

their formation. The surface of a dune is very apt to be covered with fine parallel ridges of sand an inch or so in height, transverse to the direction of the prevailing wind, and called *ripple-marks*, because they are similar to the fine parallel ridges made on sandy bottoms by the action of the waves. Dunes are found along low coast lines in all parts of the world, where the sand made by the waves is washed ashore, and, caught up by the prevailing winds

Fig. 5. — View of sand-dunes, near Mammoth Station, Cal., showing ripple-marks. W. C. Mendenhall, U. S. Geol. Surv.

from the ocean, is drifted inland and accumulated. Thus they occur at various places along the Atlantic coast, and on the Pacific shore of the United States; in England; on the shores of the Baltic Sea; in Holland, France, etc. In the same way they are produced on the shore-lines of large lakes or inland seas; thus the southern end of Lake Michigan is fringed with high sand-dunes.

In arid regions where the soil, formed by the disintegration of the underlying rocks, is not held down by a sufficiently protective mantle of vegetation and is therefore easily moved by the wind and accumulated in favorable places, sand-dunes are a common phenomenon. They are thus characteristic features of desert landscapes, and the great deserts of central Asia, of Africa, of Australia, and those in western America are in considerable part covered with them. The areas from which the soil is moved are left as barren stony wastes.

Shape of Dunes. — The shape of the dune varies according to local circumstances, but a very common and rather typical form is seen outlined in the ground plan in Fig. 6. The arrow shows the direction of the prevailing winds. The windward side *a* has a gentle slope whose angle depends on the average strength of the wind; if it is very strong the sand will be carried up a steeper angle of slope. The dune is terminated by a rather sharp crest. On the leeward side *b* is a relative calm with a back eddy and the sand is here dropped; the angle of slope is here much steeper, being that at which sand will lie at rest without sliding down, from 20° to 25° * the down-sliding being, in part, arrested by the eddy. From this ideal condition the shape is being constantly modified more or less by shifting winds.

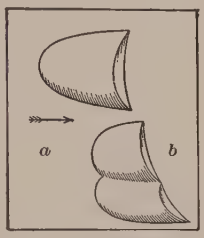


Fig. 6. — Shapes of sand-dunes.

Migration of Dunes. — The transference of material from the windward to the leeward side causes dunes to march steadily in the direction of the prevailing wind, unless the sand is held down by a

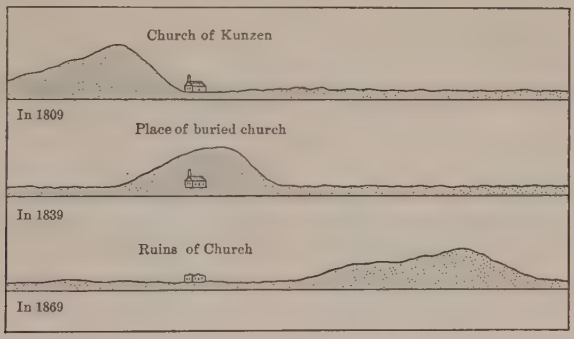


Fig. 7. — Movement of a sand-dune during 60 years on the east shore of the Baltic Sea at the village of Kunzen. (After Berendt.)

mat of vegetation. As the sand is lifted by the wind and then dropped, the dunes maintain their height, or, with increase of material, grow higher. Along exposed coasts the prevailing winds are from the sea and thus the shore-line, especially where low and sandy, is apt to have a fringing belt of sand-dunes which may vary from a few hundred yards, or less, to a number of miles in width. They

* The steepest angle of repose that could be obtained by carefully pouring dry dune sand from San Francisco was about 30°, in dunes this is probably not often obtained.

tend constantly to move inland, the rate of movement depending on the force of the wind; in Denmark they have been found to move as much as 24 feet in a year, in other places 15 feet or less. In their march they cover and destroy arable lands, forests, and even villages and towns, leaving ruined sandy wastes behind them. Many instances of this could be cited from various parts of the world; some of the best known are from the shores of the Baltic Sea. See Fig. 7. In the deserts of central Asia Sven Hedin, the explorer, found ruined cities of an ancient civilization emerging from the sand, which a long period ago had overwhelmed them and the fertile lands which must have once supported them.

Fig. 8. — Forest overwhelmed, covered, killed, and then left exposed by marching sand-dunes. Manitou Island, Lake Michigan. I. C. Russell, U. S. Geol. Surv.

When covered with vegetation the dunes are stationary, or move more slowly, and therefore when they become a menace attempts are usually made, and often successfully, to induce such a growth upon them. This has been done in places on the Pacific coast, and it is stated that the effect of starting forest growth on the dunes along the coast of France to render them stationary resulted, not only in accomplishing this purpose, but so profitably in regard to the forest itself, as to greatly help in inducing reforestation elsewhere.

Loess. — In the valley of the Rhine and other rivers of northern Europe there occur in places considerable deposits, on the valley

sides, and even up to great heights on the slopes of mountains, of a peculiar structureless, yellowish-brown earth to which the name of *loess* has been given. The particles of quartz, feldspar, clay, calcite, mica, and other minerals * composing it are much finer than those of ordinary sand and are sharply angular, showing no sign of rounding by wear as the larger grains carried by wind and water do. Nor do the deposits exhibit the lines of stratification, or bedding, which are characteristic, as will be shown later, of the sediments laid down by water. Moreover the shells found in it are those of land forms, like snails, and the bones those of land animals. These facts, and its irregular distribution at various heights, appear to prove that it is a deposit which was formed on land, not in water.

The loess is full of small, slender, perpendicular holes, or tubes, which give it a vertical cleavage, so that it commonly presents in many places upright bluffs along ravines and river courses, which, depending on the thickness of the deposit, may be of considerable height.

Similar deposits are found in the United States in the central part of the Mississippi valley, especially in the states of Iowa, Kansas and Nebraska, and covering in sum total thousands of square miles. They also occur in the states of Oregon and Washington and other parts of the western United States. The thickness is usually not great; from 10–20 feet perhaps, sometimes as much as 100.

It is now generally believed that the loess of Europe and America is for the most part an eolian deposit, dust blown and dropped in favoring localities by the wind, and accumulated during long periods of time. The origin of the material is supposed to be as follows: It is known that in a recent period, as will be shown later, large areas of North America and Europe were covered with thick and moving sheets of ice which ground up the underlying rock and soil. The fine material thus produced was carried outward and beyond by waters resulting from the melting of the ice, and when spread out in the open valleys and land stretches it was, when dry, whirled away in dust clouds by the wind and deposited. The stems and roots of successive generations of grasses growing on the deposits and buried by the rising accumulations have by their decay produced the slender vertical tubes which have been mentioned above as occurring in the loess.

The greatest development of the loess is in Asia, in Turkestan, Mongolia, and especially China. The greater part of northern central China is covered with it, and the yellow earth washed down by the rain and streams colors the waters

* See Appendix A for description of these minerals.

of the great river Hoangho (Yellow River), and the sea (Yellow Sea) into which it discharges, and has thus occasioned their names. The bluffs, which it forms, are in places 500 feet high, and its thickness is estimated to be greater than this in some parts. In the river valleys it commonly forms a series of terraces, rising step-like above one another, with upright bluffs facing the river. The Chinese, who cultivate the arable soil it forms, have cut back into these bluffs and fashioned cave-like dwellings for themselves, which have been inhabited for centuries, as seen in Fig. 9. Owing to the vertical cleavage and softness of the loess the streams, even small ones, run in steep-walled gorges, while the roads and paths which have been used for centuries, by the rapid wear of the soft material and

Fig. 9. — Dwellings in the Loess in Shansi, China. Photo by Baily Willis, U. S. Nat. Mus.

its constant removal, when thus loosened by wind and rain wash, have also become small canyons. The whole country is thus dissected by innumerable ravines and gorges, which render it impassable to the traveler, unless accompanied by a guide.

The loess of China was held by von Richthofen, the German geologist and explorer, to have been produced by dust, continually borne from the great deserts of central Asia during long ages by the prevailing winds, and deposited in the basins and valleys where it now lies. Some hold however that the loess, both here and elsewhere, is in large measure, if not entirely, a deposit made by water.

Other geological effects of the atmosphere in accumulating deposits of volcanic dust, of tornadoes levelling forests and thereby impeding drainage, etc., might be mentioned, but these are of less importance. The phases described illustrate sufficiently its mechanical work and we are now ready to consider its chemical action,

especially when aided by water acting both chemically and mechanically. This is seen in the phenomenon called weathering.

Rock Weathering and Soil Formation

The Soil Mantle. — The outer shell of the earth, as we know it, is everywhere composed of more or less firm solid rock, commonly called for any particular place "country rock" or "bed-rock." Nearly everywhere this is covered by a mantle of loose material of variable thickness which passes under a variety of names, but which for convenience, where exposed to the air, we may designate as "soil." Here and there in ledges, precipices, and the craggy tops of hills and mountains, we may see the bed-rock projecting above this mantle of soil. As compared with the earth, as a whole, it is a mere film on its outer surface and might be compared to the film of tarnish a polished metal ball would acquire on exposure to moist air. The part which it plays in geological processes will be considered later; it is our purpose now to study its origin, for in its formation is seen one of the most important functions of the atmosphere as a geological agent.

Weathering. — The outer rocky crust, or bed-rock, is everywhere more or less shattered; it is penetrated in all directions by cracks and fissures, some great, some small. Even the mineral grains are more or less filled with cracks, often cleavage cracks. Into such fissures the air enters, carrying with it the various gases and the insensible moisture it contains. If the moisture becomes sensible, as in the form of rain, then water enters them and by the force of capillary attraction may be drawn into the most minute crevices. Since the air contains water, and water, as a liquid, has the power of dissolving gases, and therefore contains those of the air, the work of these agencies, air and water, is so closely associated that we cannot draw any sharp line between them. They work together to cause rock to decay and turn into soil and in this they are powerfully aided by changes of temperature, by heat and by cold, and to a lesser degree by the action of plants and animals. The work is partly mechanical, partly chemical, and taken altogether it comprises a rather complex set of processes which are conveniently designated under the name of *weathering*. Some of these may be considered separately.

Heat and Cold. — The daily range of temperature, the difference between the heat of day and the cold of night, may be 50° or even as much as 75°; the annual range, between the cold of winter and the heat of summer may be 100°, or even as much as 150°. Where

the rock masses are exposed to such changes of temperature they are powerfully, irresistibly expanded and contracted, see Fig. 10. A mass of granite 100 feet long by a change of 150° would expand one inch. Moreover the unlike mineral grains composing most rocks do not expand equally, and hence interior stresses are produced. Unable to withstand such actions the rocks are ruptured and break into smaller pieces. Such effects are not felt deeply, for rocks are poor conductors of heat, and thus when bed-rock is exposed the

Fig. 10. — Buckling in sandstone layers due to expansion from heating by the sun. Wyoming. E. E. Smith, U. S. Geol. Surv.

back and forth expansion movements of the surface layer tend to shear it loose from the unchanging mass below. Thus surface layers scale off, or exfoliate, as seen in Fig. 11. By this process in those places where great extremes of temperature occur, as in deserts and in semi-arid regions, the exposed rock masses are broken and rounded off.

Effect of Frost. — In cold countries the effects described above are greatly aided by the action of frost. Water fills the crevices and on freezing expands, splitting the rocks with great force. This action is best seen in high mountains whose slopes are in different places and sometimes entirely, covered with such broken rock fragments, commonly called "slide rock." Where such masses of débris accumulate at the foot of a cliff they are called *talus*, as seen in Fig. 12. In high mountain ranges the effect of frost in carving and shaping the peaks and pinnacles of rock is very great.

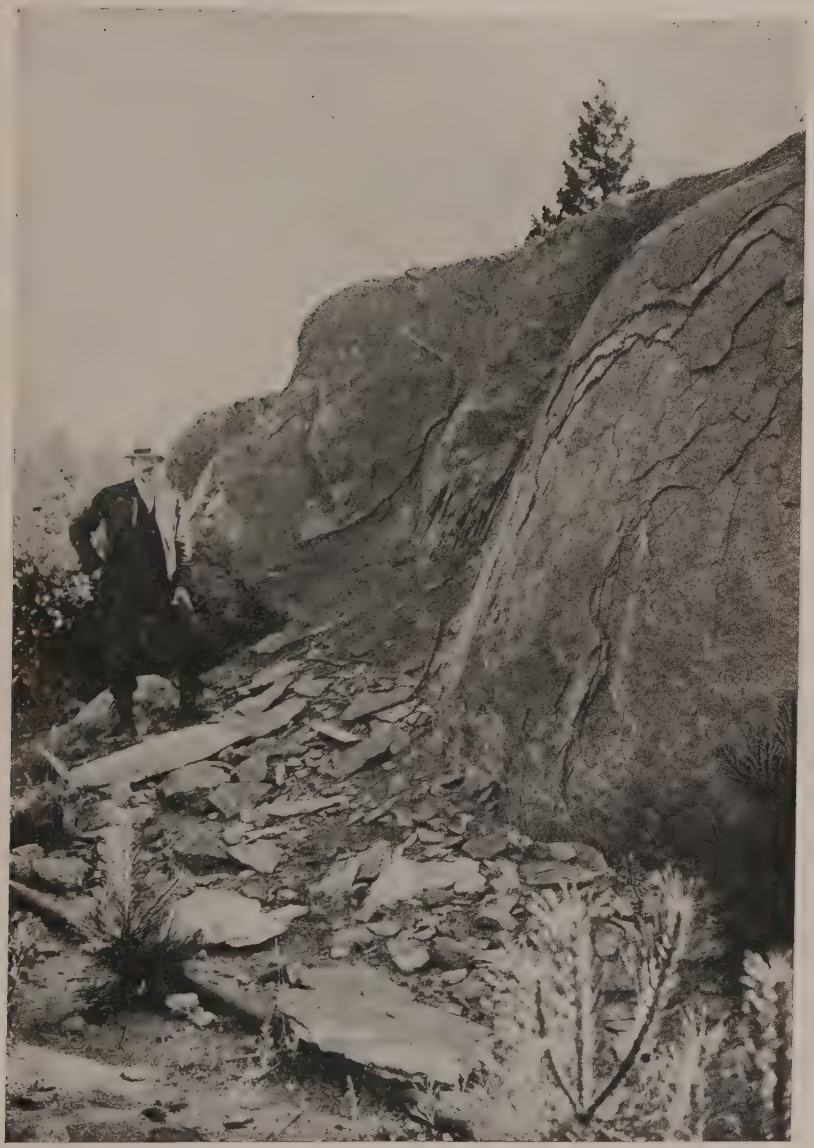


Fig. 11. — Exfoliation, or scaling of rock, by alternate expansion and contraction of surface layers. Nevada City, Cal. G. K. Gilbert, U. S. Geol. Surv.

The term *slide-rock* implies any loose fragmental rock lying on a slope, while *talus* is restricted to those cases where there is a projecting mass, or cliff, of country rock above from which the débris has evidently been derived. A talus

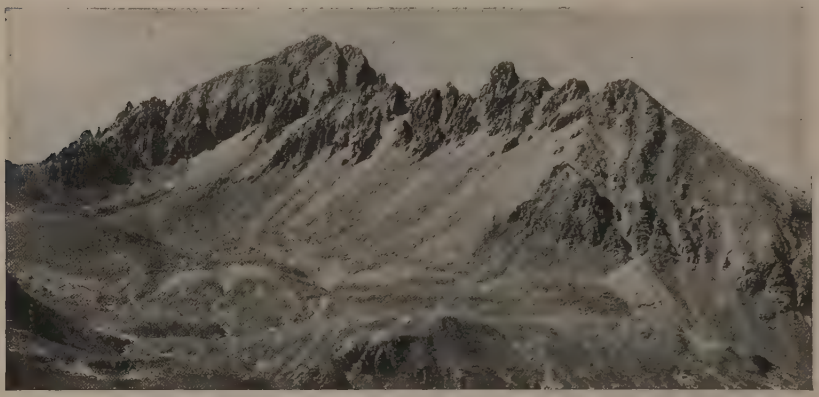


Fig. 12. — Rock disintegration and weathering in high altitudes, with formation of long talus slopes of slide rock. Mt. Sneffels, Colorado. W. Cross, U. S. Geol. Surv.

should not be conceived as having a section like that of *abc* in Fig. 13, a case which can rarely happen, but rather like that of *a'b'c'*. A talus indeed is often only a rather thin sheet of fragmental material resting on sloping bed-rock, which may here and there project through it. As the destruction of the cliff *a'* goes on it may retreat until its contour is like that of *b'c'* beneath the talus. It may also be covered with the rising talus until the latter forms the whole slope of the mountain. Ordinarily the coarsest material, blocks of rock, is seen at the top of the talus slope; as these break up into finer material this is washed down, descends, and may gradually assume a more gentle slope; this lower part is frequently made of soil with vegetation growing on it. In warm regions it is chiefly the expansion and contraction which breaks the bed-rock and forms the talus; in cold countries the action of frost is more important.

Fig. 13. — Section through a cliff and its talus.

Chemical Work in Weathering. — The mechanical breaking up of rock and its conversion into soil is powerfully aided by chemical processes. In these water, oxygen, and carbon dioxide are the chief agents. By them the chemical compounds forming the minerals of the rocks are attacked and in a great measure changed into new substances. The oxygen converts those of a lower state of oxidation into ones of a higher; water, besides being a solvent, enters into combination in many new compounds; carbon dioxide, with the water, helps to bring substances into solution and to change them into carbonates. Thus in a general way we may say that as

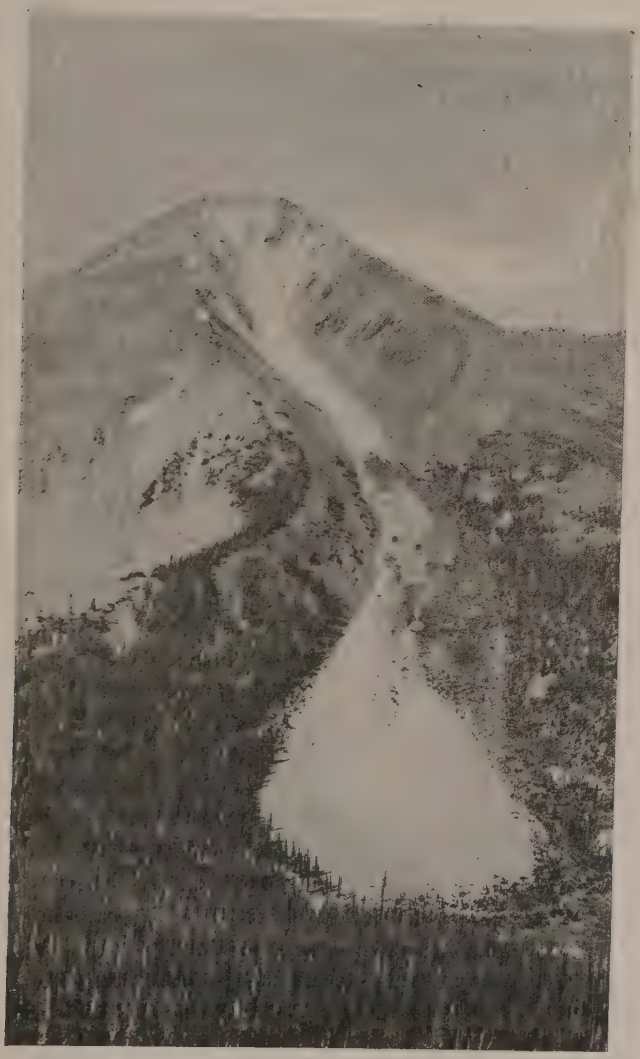


Fig. 14. — Talus cone at the foot of a gulch. Foot of talus to mountain top is 3000 feet in vertical height and over a mile in distance. Mt. Ætna, Colorado. R. D. Crawford, Geol. Surv. of Colo.

a result the new minerals formed in the place of the old ones are more highly oxidized and contain water or carbonic acid.

This may be illustrated as follows: One of the most important of the rock-making minerals is feldspar * of which there are several varieties; one of these known as orthoclase consists of oxides of silica, alumina, and potash. When this is attacked by water containing carbon dioxide in solution the following reaction takes place.

Orthoclase	+ Water	+ Carb. diox.	yields	Kaolin	+ Quartz	+ Potas. Carb.
$2\,KAlSi_3O_8$	+ $2\,H_2O$	+ CO_2	=	$H_4Al_2Si_2O_9$	+ $4\,SiO_2$	+ K_2CO_3

This is one of the most important reactions which takes place in nature, since the existence of life is largely dependent upon it. Animal life depends on vegetable life, and the latter upon the soil; kaolin — commonly called *clay* — is an essential ingredient of good soils, while carbonate of potash is a necessary food of plant life; by this process the potash in the rocks is removed from the feldspar, converted into a soluble form, and vegetation is able to assimilate it.

Solvent Action of Carbonic Acid. — Some rocks, such as limestone, are composed almost entirely of calcium carbonate, $CaCO_3$, which forms the mineral known as *calcite*, while in others this substance acts as a cement to bind the grains to one another, as in some sandstones which are made of grains of quartz sand thus held together. Calcium carbonate is nearly insoluble in pure water, but when carbon dioxide gas, CO_2, is dissolved in it there is formed an aqueous solution of carbonic acid, H_2CO_3. This attacks the calcium carbonate and converts it into calcium bicarbonate, $H_2Ca(CO_3)_2$ which is quite soluble in water. The natural surface waters, like rain, contain more or less carbonic acid in solution and more is supplied by decaying vegetation; through its action the binding material is dissolved, the grains loosen, and the rock crumbles and breaks down into soil. In the case of limestone the greater part of the rock may go into solution and be carried away, leaving only the insoluble impurities, usually clay, to remain behind as the resultant soil. This solvent action of carbonic acid on carbonates is one of great geological importance; we are here only concerned with it in so far as it helps to make soil; what it accomplishes in other ways will be treated in a later place.

Soil in Situ. — The process of weathering is superficial and is very slow; if the bed-rock were perfectly firm, solid, and continuous it would gradually cease, since the underlying rock would be protected by the mantle of soil upon it. It is a common thing, however, for this mantle to be removed as fast as formed, by agencies which will presently be described, exposing fresh surfaces to attack.

* See Appendix A.

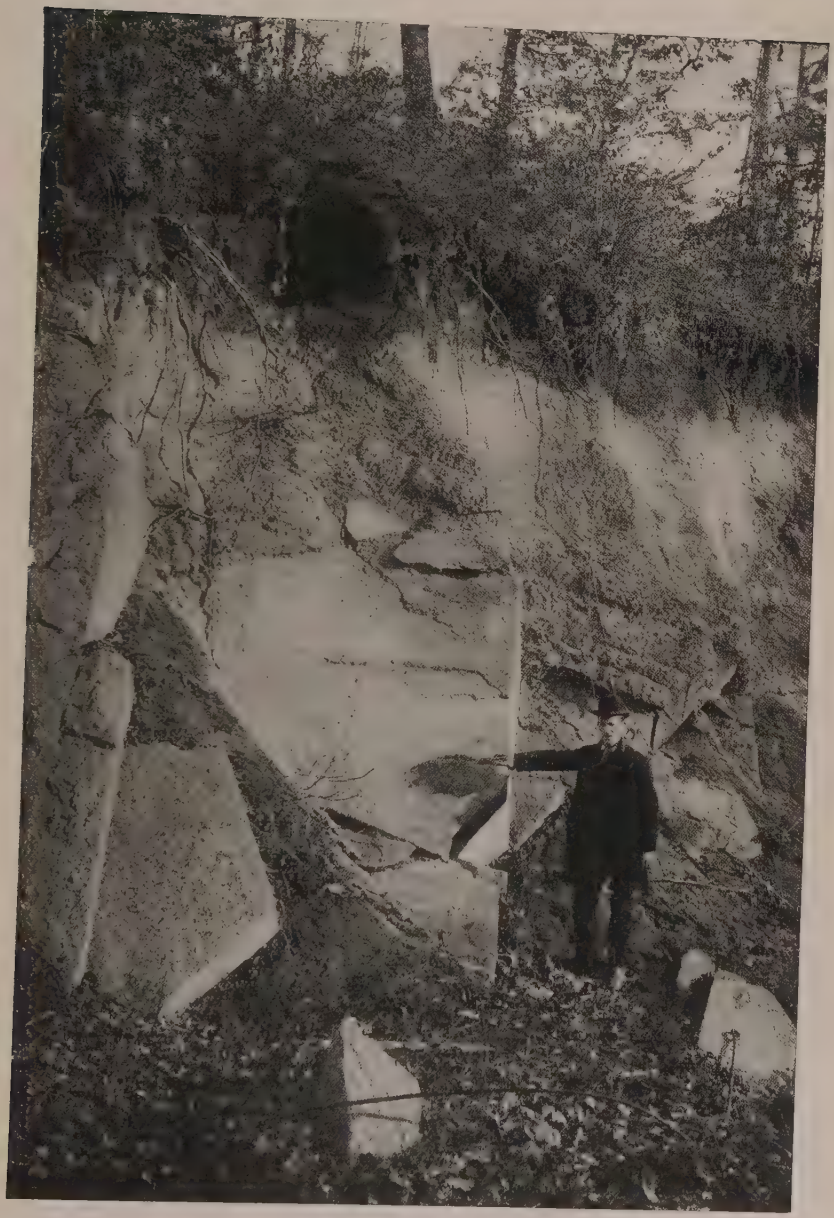


Fig. 15. — Illustrates the formation of soil in place by rock weathering and decay. The material graduates from firm rock below, through rotten rock and then subsoil, to true soil above. The transition is gradual without break. The true soil above is colored dark by decayed organic matter. G. P. Merrill, U. S. Nat. Mus.

Even where this does not happen, on account of the fissured and cracked condition of rocks, previously mentioned, the agents of weathering may be able to penetrate quite deeply and form considerable depths of soil. Where this has taken place, if one examines downward, as in wells or road cuttings, one finds that the perfect soil at the top, supporting vegetation, gradually passes into a more or less coarse, gravelly material full of angular bits of rotten rock; this is known as the *sub-soil*. The latter passes downward imperceptibly into decayed rock which crumbles more or less easily and this in the same gradual way into the firm, solid, unaltered bed-rock. Thus there is a gradual transition from perfect soil above to perfect rock below and this proves that the soil has been formed in the place where it now lies by the decomposition of the local rock. Thus these changes can be conveniently divided into the four stages mentioned: *a*, soil; *b*, sub-soil; *c*, altered rock; *d*, unchanged rock. When the soil lies where it has been made it is termed "in place" or soil *in situ*. An illustration of this gradual change from rock below to soil above may be seen in Fig. 15.

The reason for making this distinction as to whether a soil has been formed *in situ*, or not, is important because over wide areas the soils are not in place, but have been brought from elsewhere, or shifted, by the action of wind, running water, moving ice, etc., as illustrated in Fig. 16. Over much of the northern

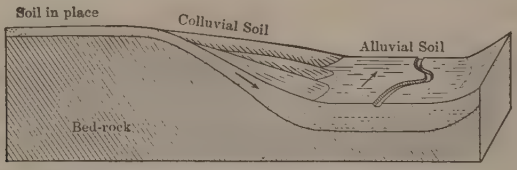


Fig. 16. — Diagram illustrating the forming and movement of soil.

United States, Canada, and northern regions generally, it will be found that there is no gradual transition from soil to rock, such as described above, but that perfect soil rests directly upon unchanged solid bed-rock. This is a clear proof that the soil has been shifted. These regions were once covered, as will be shown later, by vast areas of moving glacial ice which ground away the rotten rock and shifted the soil. In the southern states and in warm and tropical countries much of the soil is *in situ* and in some places it is as much as several hundred feet deep.

Kinds of Soil. — The nature of the soil produced by the decay of rocks depends chiefly upon the kinds of mineral grains of which they are composed. The more important of these minerals are *feldspar*, *quartz*, *calcite* and *clay*, which have been mentioned previously and their compositions given. Feldspar changes to clay, while

quartz on the other hand is not affected by weathering. Calcite, $CaCO_3$, is soluble under the conditions which have been stated. In addition to these there are many other kinds of minerals, such as the silicates of iron and magnesia forming substances like hornblende, dark mica, etc., but these are of lesser importance. Thus when rocks like granite, which is chiefly composed of a mixture of quartz and feldspar, are thoroughly decomposed into soil the latter consists of clay intermingled with quartz grains. A pure feldspar rock would yield only clay; while a pure sandstone would give only sand by disintegration. According to the size of the particles which compose the broken and disintegrated rock the following gradations are recognized: Pieces of loose rock from the size of a small melon up are termed *bowlders;* those larger than peas are called *gravel.* Pieces smaller than peas, but which do not cohere when wet, are *sand,* while the finest material, which can be carried by the wind, is *dust,* and this generally coheres when wet and is termed *silt,* or *mud* or *clay,* according to its character. Ordinary soils are composed of variable mixtures of sand, and these finer materials. We may roughly classify them into the following groups:

Sand, composed of sand grains, mostly quartz, without clay.
Loam, mixtures of sand and clay.
Clay, the finest material, mostly kaolin, without sand.

Of these loam is most easily worked and makes the best soil; clay is next, but is apt to be stiff and difficult to work, while sandy soils are usually light and also poor for the growth of vegetation.

Fig. 17. — Residual bowlder resting on bedrock, "Balanced Rock," Garden of the Gods, Colorado.

The red and yellow colors which many soils possess are due to the hydrous oxides of iron produced by the decay and oxidation of the original minerals in the rocks consisting of iron oxides and silicates. A dark or black color, best seen in swampy soils, is due to carbonaceous material, resulting from the decay of vegetation. This substance, which is present to some degree in most arable soils, is known as *humus* and those very rich in it are

called *muck*. When a soil contains a considerable quantity of carbonate of lime it is termed a *marl*. Thus *sands*, *loams*, *clays*, *mucks*, and *marls* are the chief kinds of soils and there are all gradations of these into one another. Owing to the presence of the dark organic matter, or to the greater oxidation of the iron compounds, and often to other reasons the top soil is apt to be much more strongly colored than the underlying subsoil.

Bowlders of Decomposition. — The change of bed-rock into soil is not apt to take place equally, either over small, or wide areas.

Fig. 18. — Residual bowlders left by decomposition and wearing away of bed-rock. The bowlders are included masses of a harder, more resistant material and of rounded shapes (concretions). This shows that residual bowlders may in some cases differ from the bed-rock on which they lie. Coalinga, Cal. R. Arnold, U. S. Geol. Surv.

For the rock mass undergoing decomposition is not everywhere uniformly cracked and fissured, allowing free access to all parts of the agents of disintegration which have been described. Moreover, some parts of the rock mass may be different in composition and texture from the rest, and thus harder, denser, more durable, or less soluble. From this it commonly happens that the soil is more or less filled with pieces of unchanged or but little altered rock which are termed *bowlders*. That such *residual* bowlders have been formed in the place where they now are is proved by their similarity in

mineral composition and appearance with the still unchanged bedrock below. But it frequently happens that bowlders are very different in character from the rock below them and this shows in most cases that they have been moved or are *transported blocks*. It may happen that, where residual bowlders of decomposition are forming, the soil about them may be removed by wind or rain wash as fast as formed, as illustrated in Fig. 17. In this case they may be left upon the surface as scattered blocks, see Fig. 18.

CHAPTER II

RAIN AND RUNNING WATER

The Rainfall. — The amount of rainfall which a country receives is dependent on a variety of factors, such as the direction of the prevailing winds; the nature of the places over which they have previously passed, as to whether these are land or water areas, and, if the former, low land, or high mountainous tracts; on the surface character of the country which receives them, whether high or low; and on other considerations as well. Thus it happens that the amount of rainfall received by the land is very unequally distributed over the world; in some places, as in Central America, it may be as much as 100 inches per year, while in the great deserts it is less than 10. In general, in North America, one may say that in the Atlantic sea-board region, and in the Southern States, the rainfall is 40 inches or more per year; as one goes westward into the Mississippi valley it diminishes to 30 inches; in the Plains region to 20 or less; in the Great Basin between the Rocky Mountains and the Sierras to 10 or less. Locally in the mountains it is increased, as these are great condensers of moisture. On the Pacific coast it increases again. Roughly speaking one may term those regions where the rainfall is 20 inches or less *semi-arid* to *arid*, those where it is greater than this *humid*. As we shall see later, the work of geologic processes, and the results of this work, are in many ways strikingly different in arid regions from those in humid ones.

The Run-off. — A part of the water which falls in rain is evaporated and passes back into the atmosphere; another part sinks into the soil and the fissured or channeled bed-rock below it and there, on its way underground to the sea, becomes an internal geologic agency whose work we shall study later. Some of this water, which thus sinks at first, reappears as springs and, joined by that which runs directly upon the surface, finds its way by means of rivers into the sea. This water which the streams carry away from the surface of the land is known as the *run-off*. The immediate part of the run-off is that which causes floods and freshets, while the springs furnish the steady supply. It has been estimated that there falls annually upon the land areas of the globe about 29,000

cubic miles of rain water and of this about 6500 cubic miles constitute the run-off. In the Mississippi basin one quarter of the total rainfall forms the run-off. It is the object of this chapter to describe the geological work performed by this run-off.

Movement of Soil Mantle: Erosion. — As has already been shown, the surface of the land is, in general, covered by a mantle of soil resting on bed-rock. Now by the action of running water, aided by gravity, this mantle of soil and crumbled rock, which, as it ordinarily appears to us, seems to be at rest, is actually in motion, considered from the geological standpoint, and is being continually urged downward into the sea, its ultimate goal. On steep mountain slopes it goes more rapidly, in valleys more slowly, while in level plains, like water in a lake, it is temporarily at rest. Its rate of motion varies from time to time and from place to place. As it moves away, its place is supplied by fresh products of rock decay, which also move in their turn, and so the process is continued, year in, year out. This formation of rock débris and its removal produce the waste of the land surface and this wasting is known under the general term of *erosion*. We may study in detail the various features of the process and the agents which perform it; chiefly they are wind, running water and moving ice; the work of the wind has been already treated; that of ice will be considered later; the work of the water is to be considered here.

Rain Wash. — It is a well-known fact that the wash of the rain continually carries away the soil, moving it from higher to lower places. The rain drops run together and form rills; these dig out gullies; the gullies run together and the larger volume of water excavates ravines or gulches. These effects are conspicuously seen on steep slopes of soft material, such as clay, and are illustrated in Fig. 19. The result of this removal of material is seen after every storm in the volume of muddy water pouring out of each gully and ravine into the larger channels below. The amount removed in a given time by this means varies greatly with a number of circumstances. For instance it varies with the character of the soil and of the bed-rock. In New England, for example, the bed-rock is hard and crystalline, the soils stony and clayey glacial deposits which resist erosion well; what the rains wash into the streams is almost entirely from the soil, while over wide areas of the Southern States and the Western Plains, the country rock consists of soft, little compacted deposits of sand and clay, whose resistance to rain wash is not much greater than that of the soil itself, or the soil is loose and deep and held only by the vegetation. Rivers draining these latter

regions are constantly turbid and filled with muddy sediment. Another feature which has a great effect upon the rate of erosion, as partly noted above, is whether the soil is covered with vegetation, or not, and this is so important that it deserves especial consideration.

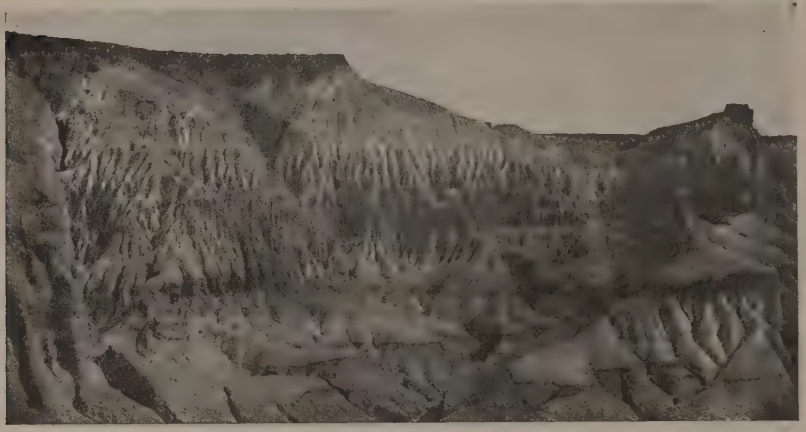


Fig. 19. — Effect of rain wash in beds of clay. Sioux Co., Neb. N. H. Darton, U. S. Geol. Surv.

Effect of Vegetation on Erosion. — Where the soil supports a rank growth of vegetation, and especially if it has a thick forest cover, erosion by rain wash and gullying is greatly hindered and it may be almost entirely prevented. There are two reasons for this: first, because the mass of roots distributed through the soil, together with the mat of organic matter on the surface, holds the soil firmly in place and enables it to resist the pressure of the moving water, and, second, because the mat of vegetation acting like a sponge absorbs the water and permits it to drain off so slowly that the destructively erosive effect of sudden rushes of water after storms is prevented. Likewise in springtime the rapid melting of the snow is hindered by the forest shade, especially when it is composed of evergreen trees. Such effects are of course most noticeable on steep slopes, among the hills and mountains. If, in the settlement and cultivation of a country, the forest cover is entirely removed from such places erosion starts at once and proceeds rapidly, as illustrated in Fig. 20, and in a variety of ways great damage may be done. It is a noticeable fact that in forest-covered countries the flow of the streams is quite regular and their waters relatively clear; in those well cleared of forests and cultivated the rivers on the other hand are subject, especially in the spring, to sudden and heavy

floods, their waters are very muddy, and they are apt to be very low, or even dry, in months of little rainfall.

This regulative action of the forests on erosion and the flow of rivers is a matter of great importance, not only from the geologic standpoint, but as vitally

Fig. 20. — After the removal of the forest cover the soil has been carried away so rapidly that the remaining trees have their roots exposed by the lowering of the surface. Southern Appalachians. U. S. Forest Service.

affecting the economic conditions of civilization. In some countries, of which Spain and northern China might be selected as examples, the improvident removal of the entire forest cover has reduced large areas, through displacement and loss of arable soil by erosion, to sterile wastes, subjected alternately to hot and baking droughts and sudden and disastrous floods. Destruction of the forests by fire may have a similar effect. Once destroyed, and the soil washed out, they may not be restored, or only with great difficulty after long periods of time. Considerable areas in the Southern States have been much impoverished in this way. In places, where density of population causes all land that can be cultivated to be valuable, terracing of hill slopes to prevent erosion is much resorted to. The yearly loss of arable soil is one of the great wastes of modern civilization that should be checked as much as possible; forests should be cultivated on all eminences and places not adapted to agriculture and their cutting carefully regulated, not alone for the timber they may furnish, but to prevent erosion and regulate the flow of streams.

Erosion in Arid Regions. — In arid and semi-arid regions the effects of erosion, as produced by rain wash and gullying, are perhaps most plainly seen. If the region is absolutely rainless there is naturally no erosion from this cause, but places where there is practically no rainfall are rare; a certain amount of rain falls even in those districts which are usually termed arid, and, as it is apt to come in heavy and violent downpours, its effect is strengthened. The lack of an adequate mantle of vegetation also helps the erosive process and permits its effects to be clearly open to our observa-

tion. This also allows the wind to perform its part of the work, as described in the preceding chapter, in transporting material from higher to lower levels where it is more accessible to the streams which carry it away, or by dropping it directly into the streams. Thus the wind, which is of small importance in humid regions, becomes a strong factor in erosive processes in arid ones.

Striking examples of such erosion are to be seen along the rivers which drain the Great Plains region. These rivers, such as the Missouri and its tributaries the Cheyenne, Platte, etc., in places run in valleys sunk a considerable distance below the general level of the country. The country rock which forms the sides of the valleys for the most part is very soft, barely consolidated clays and sands, and thus easily cut by rain wash and gullying. The result is, that on either side of the stream, from the bottom-land by the river to the bench-land forming the plain, lies a gradually rising belt of country, cut in the most intricate fashion by systems of gullies, gulches, and ravines, with spurs, knobs, and sharp ridges separating them as illustrated in Fig. 21. Such tracts of country are known as *Bad-lands*, from the difficulty experienced in traversing them.

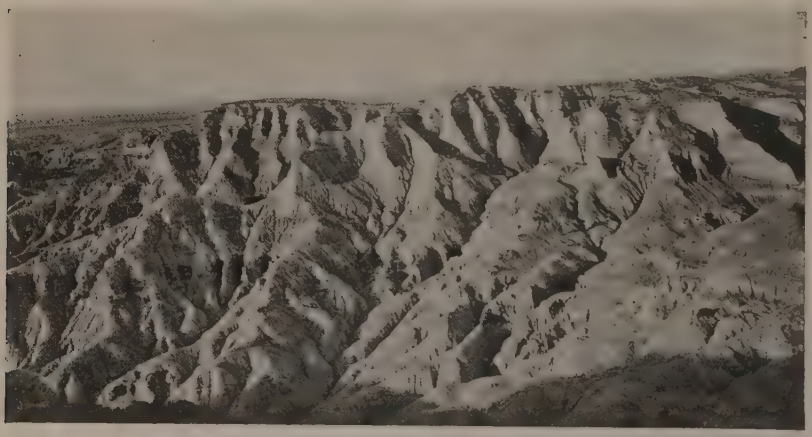


Fig. 21. — Bad-lands, near Scott's Bluff. Neb. N. H. Darton, U. S. Geol. Surv.

It is to be noted that in general, where not merely the top soil but the underlying rock is concerned in erosion, the softer the material, the more striking become the effects of gullying and the rougher the resultant topography. It is as if, in the hollowing out of a trough from a block of wood with a gouge, a very soft kind of wood were used; then with each stroke the hollow chisel would bite deeply and the intervening ridges would be pronounced. In hard crystalline rocks the rate of erosion is dependent on that of weathering and disintegration and hence, except in very high mountains where these processes are rapid, the forms of erosion are more smooth and subdued.

Remnants of Erosion. — It has been explained under the description of the weathering of rocks that this process was not every-

where uniform. All parts are not equally accessible by cracks and fissures to the agencies which produce decay and some parts may be harder and more resistant than others. Since erosion consists in the loosening of the rock substance and its removal, it commonly happens in regions undergoing the process that, due to this want of uniformity, there are projecting masses of the more resistant material. This is illustrated in Fig. 22, as occurring on a small scale, but such features are found of all sizes up to veritable mountains. Moreover, erosion is less rapid in areas between streams, because the slopes may be more gentle where the valleys are not cut down, and the material must be transported farther; this applies especially in the level plains country. Large isolated masses are known in the western regions as *buttes* and are

Fig. 22. — Hard masses of ironstone in beds of soft sandstone have shielded the rock below them from erosion and produced pillars. Monument Park, Colo.

Fig. 23. — Red Butte, Bell Ranch, New Mex. W. T. Lee, U. S. Geol. Surv.

illustrated in Fig. 23; they have been generally made in these ways and are remnants of erosion. When such an elevation is broad and

flat topped it is termed a *mesa*, from the Spanish, meaning "table" and referring to its table-land character; it is also a remnant of erosion. Such mesas are generally capped by a layer of hard rock, often lava, which has protected the softer layers beneath. These features and the rugged sculpturing of mountains all testify to the great work of erosion and the amount of material carried away.

Rivers and River Valleys

Gullies run into ravines or gulches, and the rivulets which drain the latter run together to form brooks and creeks which in turn unite to make rivers. The rivers then are the main channels of drainage and they are the chief factors in carrying away the waste of the land. They are to be regarded as the great trunk lines of transportation for the products of erosion which are delivered to them by their tributaries. In addition they are themselves powerful agents of erosion; in them the work of running water as a geological agency is most conspicuously displayed and this work in its varied features and the results of it may now be considered.

Course of a River; its Grade. — If we should think of a typical river we should imagine it rising in lofty mountains through the union of many impetuous streams or dashing torrents; gathering headway it rolls rapidly through the belt of lower hilly country and emerges upon wide plains through which it wanders in many curves in a quiet and steady flow to the sea. Its grade, as one follows it from source to sea, would be indicated by a changing curve which approaches the angle of repose, that is, a slope of twenty to thirty degrees, which becomes less and less until it is nearly horizontal at the river's mouth, as illustrated in Fig. 24.

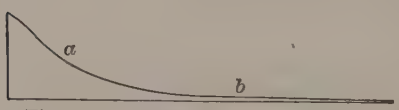


Fig. 24. — Profile of a river showing its grade.

While we think of this as the ideal course of a river, and it is typical of many of the great rivers of the world such as the Amazon and the Ganges and of a great number of smaller ones of which the Po in Italy might serve as an example, one constantly finds variations from the type. Thus the Mississippi does not rise in a mountainous country but in a moderately elevated region of low relief and it has a very uniform grade to the sea; in other cases where rivers rise in mountains near the sea the lower plains district, corresponding to *b* of Fig. 24, may be very short or wanting. The rivers of the northern Atlantic coast are mostly between these extremes and their courses lie between *a* and *b*; those of the Southern States are more nearly typical, since they rise in the Appalachian Mountains and flow out upon the Atlantic coastal plain.

River Erosion — Corrasion

If we consider the whole course of a typical river from its source to the sea we find that it performs both destructive and constructive work. The former is a work of erosion and is done chiefly in the upper steeper part of its course, that portion which is indicated by *a* in Fig. 24; we will examine first the conditions under which this is carried on while the constructive work will be treated later. In the first place it is clear that, unlike rain wash and gullying, which are a general effect over the whole land area like the result of weathering, the erosion of rivers is local and confined to the bottom and sides of the channels over which the water passes. A river may be compared to a sinuous, flexible and endless file, ever moving forward in one direction and by means of the moving sand or gravel rasping away the country rock beneath and beside it, thus cutting an ever-deepening trench. This particular phase of a river's work is called *corrasion*. The effectiveness with which a river corrades depends on several closely related things; on the tools with which the river has to work, on the amount of them, on the swiftness of its current, and on the nature of the country rock with which it has to deal. These various factors may be examined in detail.

The River's Tools. — Clear water moving over rock surfaces erodes but very little. It has a certain solvent power and may thus slowly dissolve and disintegrate rocks and in this action can be aided by substances carried in solution, especially carbonic acid. In this case the rock which is chiefly attacked is limestone, composed of carbonate of lime, and for reasons which have been previously explained (p. 24). This is, however, a chemical process, rather than mechanical erosion, or corrasion. In order to corrade a river must have tools and these are supplied by the sand and silt which it carries, and by the gravel and pebbles it can move if swift enough, either in its regular flow, or in times of flood, see Fig. 25. This material is supplied to the river chiefly by rain wash and by its tributaries, but in regions of soft material the stream may also obtain it directly by wearing and undermining the sides of its channel. If its banks are steep, or even cliff-like, the natural talus which would form at the foot of such a slope is seized by the river and carried away to be used as its tools. It is by the striking, bumping, and grinding action of this material, carried along by the current, that the river is able to cut away the rocks over which it runs and to deepen its channel.

In this process the material carried by the river is itself necessarily worn, has its sharp angles removed and becomes rounded or spheroidal, — a form characteristic of the river's tools. Thus, if we find river gravels which consist of hard, well rounded pebbles, we infer the material has been transported a long distance; on the other hand if it is composed of angular bits of rock and its situation shows that it has been transported we infer that the distance must have been short.

Fig. 25. — River bed full of more or less rounded bowlders showing the tools with which the stream works. Big Creek, Haywood Co., N. C. A. Keith, U. S. Geol. Surv.

Amount and Size of Material Carried. — Up to a certain point an increase in the amount of grinding material supplied to a river with a given velocity of current aids in its erosive power. Beyond this point an increase is not effective for the reason that the strength of the current is so consumed in the operation of transporting that the check, given by a tendency to erode, would cause the river to deposit instead. This is further discussed under transportation. Since the eroding power depends on the strength of the blow with which the moving particles strike it is clear that this in turn depends upon their momentum, that is, upon their mass multiplied by the velocity. Hence for a constant velocity the greater the mass of the particles, that is, the larger and heavier they may be, the more effective agents of erosion they become. Thus in a stream carrying intermingled grains of sand and dust-like particles of clay the sand is the really effective agent.

Swiftness; Law of Erosive Power. — It is quite obvious from the preceding paragraph that other things being equal, the swifter a current is the more rapidly it will erode. For, in a given time, not only will the number of eroding particles passing over a rock surface be increased with a swifter current, but the fact that each particle is moving more rapidly will aid its effectiveness. This may be formulated as a law in definite form as follows: *The erosive power of a current varies as the square of the velocity.* That this is true may be easily proved. If we think of an obstacle in the stream, such for instance as the abutment of a bridge, which is being eroded by the impact of sand grains moving by the current and imagine the velocity to be doubled, then on a given surface, for each moment of time, twice as many sand grains will strike as before and each with a velocity twice as great. The effect will therefore be four times as great. If the velocity is three times as great, three times as many grains will strike, each with a trebled velocity, and the effect will be nine times as great. Therefore the effect varies as the square of the velocity.

Character of the Country Rock. — It is quite evident that if a stream passes through a region whose underlying rock masses are relatively soft or of little coherence it will erode much more rapidly than in a region of very durable rocks. This of course applies as well to general erosion as to those particular surfaces affected by the moving water of the stream alone. Examples of this, as previously stated, are seen in the rivers of New England and eastern Canada, which, flowing over hard crystalline rocks, are relatively clear compared with those of the Southern Atlantic States and of the Great Plains which pass through regions of soft material and are turbid with the products of rapid erosion.

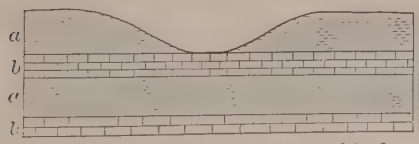


Fig. 26. — Erosion in horizontal beds.

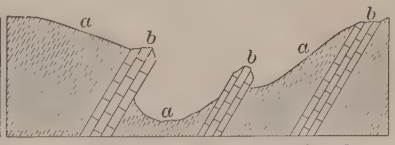


Fig. 27. — Erosion in inclined beds.

The structure of the rock masses has also much to do with the rapidity of erosion. Thus if they are greatly jointed, that is, filled with cracks and fissures, the progress of erosion is greatly aided. If they consist of alternately hard and soft layers, as is often the case, the position of these layers has a great effect in determining the rate of erosion. Thus in Fig. 26 when the hard layer, or bed, *b*, is reached it serves as a floor for the stream and erosion proceeds slowly until it is worn through; in Fig. 27 the stream eats its way downward along the soft

beds, *a*, and the hard ones, *b*, losing their support by undermining, break away in pieces and are worn and carried away. Thus, in this case, the rate is determined by the soft, not by the hard layers.

Transportation; the River's Burden

A river not only erodes, but also transports and the material carried by it forms its load or burden. While the greater part of this is carried mechanically in suspension, a very considerable portion is transported chemically in solution, while still another part is rolled along the bottom. The ultimate goal of the river is the sea into which, at the end of its journey, its burden is deposited and transferred. The various features of this work demand consideration.

Material in Suspension. — The size of the particles that a river is able to carry in suspension depends on several things; on the character of a river's current, on its swiftness, and on the relative weight or specific gravity of the particles. With respect to the first of these, if the mass of water forming the current moved forward in a perfectly uniform and homogeneous manner, each particle of water from side to side and from top to bottom moving forward with the same velocity as every other particle, only the very finest material, such as microscopic granules of clay, would remain any length of time in suspension. A sand grain dropped into the stream would sink to the bottom and there remain at rest, unless the stream were strong enough to roll it along. But the current of streams is not of this character. The more central portions are moving more swiftly, sliding over those toward the bottom and sides, while there is a constant interweaving of swifter sub-currents up and down and toward the sides and even backward, forming eddies or whirling movements. The whole effect is like the stirring of water in a glass. Sand at the bottom is quickly lifted and kept in suspension by these movements and thus carried along.

When particles in suspension in pure water attain a certain degree of fineness their settling, even when the water is still, becomes very slow. Thus, as shown by the experiments of Brewer, river waters, such as that of the Mississippi, carrying fine clay particles may remain turbid for many years. In such cases with increasing fineness there seems to be no limit in a practical way between material in suspension and that in solution, however different these may be in theory. If such waters containing clay in suspension be rendered salt and agitated the clay curdles or coagulates into lumps and is quickly deposited, leaving the liquid clear. Thus the clay of river waters, on their attaining and mingling with the salt water of the sea, is deposited on the bottom.

Velocity and Transportation. — It is well known that the swifter a current is the larger and heavier masses it can transport. Thus it

has been found that a current running a fifth of a mile in an hour will carry fine clay; one running half a mile in an hour will transport sand; one of a mile an hour will roll along medium-sized gravel, while one of two miles an hour will sweep along pebbles the size of an egg. Reduced to mathematical form it may be stated that *the transporting power of a current varies as the sixth power of the velocity.* This seems extraordinary but may be easily demonstrated. Suppose the problem to be stated as follows: if a current of a given velocity is just able to move a cube *a*, Fig. 28, what will be the comparative size of the *cube* which a current of twice this velocity can move? Now it has been previously shown that if the velocity of

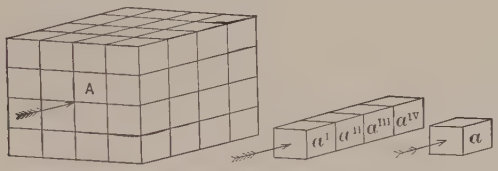


Fig. 28. — Diagram proving that if the velocity is doubled the transporting power is 64 times as great.

the current is doubled its striking force is four times as great, because in a given moment of time twice as much water strikes on the cube face of *a* and each particle of water has twice the velocity. The effect of the doubled current being thus four times as great it could move, striking on the cube face *a*, four such cubes a^{i} a^{ii} a^{iii} a^{iv} placed one behind the other to form a four-sided prism. If the current could move one, it could, within limits, move any number of such prisms endwise. But the problem was, how much larger *a cube* could it move? Now it is clear that 16 of these prisms piled together as in Fig. 28 would form a cube and the current striking on the face *A* would just move it. It can be readily seen however that the new cube *A* is 64 times as great as the original cube *a*. But 64 equals the sixth power of two. If the velocity of the current were trebled then the striking force would be 9 times as great, for three times as much water would strike in a unit of time with three times the velocity; this would move a prism 9 cubes long and it would require 81 such prisms to be piled together to form a cube. But such a cube would be 729 times as large as the original one and 729 equals the sixth power of three. Therefore the transporting power varies as the sixth power of the velocity.

With low velocities of less than a mile an hour and with fine particles this law of increase, although equally applicable, does not seem very striking. Thus sand grains may be a hundred, or a thousand fold, as large as those of fine silts

or muds and require a doubled or trebled velocity to move them. But with increasing speeds of miles per hour the effect becomes very marked and this explains why rapid streams of five miles per hour are able to move small bowlders, while sudden floods in narrow valleys, caused by torrential downpours of rain or the bursting of dams, are able to carry with them huge masses of earth and rocks, sweep away bridges and other structures, and cause great damage; see Fig. 29.

Fig. 29. — In times of flood a stream is able to carry masses and perform work vastly greater than under ordinary conditions, as here shown by the results of flooding. Manti Creek, Utah. H. Gannett, U. S. Geol. Surv.

Effect of Specific Gravity. — The size of the particle that a stream of a given velocity is able to carry depends on the specific gravity of the materials composing the particle. A familiar example of this is seen in that a lead sinker is able to remain at rest on the bottom of a stream which carries away pebbles of an equal size. A practical application of importance is found in the fact that in placer mining, which consists in extracting gold from river sands and gravels, excessively fine particles of the precious metal are mixed with vastly larger ones of the sand and gravel; the water, on account of the high specific gravity of the gold, being unable to transport it. Hence if the gold grains are relatively coarse and angular, that is unworn, it is inferred that they cannot have been transported far from the original lodes or rocks which contained them and from which they were

derived by erosion. The specific gravity of the great mass of material obtained by erosion and carried by rivers lies between 2.5 and 3.0, that is, it is that much heavier than an equal volume of water. It should also be remembered that a body immersed in water loses weight equal to that of the volume of water displaced, and this greatly aids the transporting power of the stream.

Transport on the River Bed. — Besides the material carried in suspension a considerable part of the river's burden is pushed, or rolled, along the bottom. What proportion of the whole this may be, cannot be accurately determined; it varies with the slope, the volume of water, and other circumstances. It has been thought that in the case of some rivers it is greater than the amount carried in suspension. From the studies which have been made on the Mississippi it is inferred that of the material which it carries into the Gulf of Mexico about 10 per cent consists of coarser detritus shoved along the bottom. It is obvious that, other things being equal, the steeper the grade a river has the larger will be the amount of the shoved material.

Burden Carried in Solution. — All river waters carry in solution salts of various kinds which have been leached from the rocks and soils of the country from which they drain. While, in a measured volume of what we call fresh water, the amount may seem relatively very small, in the aggregate, the weight of material thus dissolved from the land and carried into the sea is enormous. It has been estimated that annually nearly 2,735,000,000 metric tons * of solid substances are thus transported into the ocean. The Mississippi carries about 120,000,000, the Hudson, a small river, 440,000 tons, the Danube over 22,000,000, the Nile nearly 17,000,000 tons. In the Mississippi the amount carried in solution is more than a quarter as large as that carried in mechanical suspension, the quantities being

406,250,000 tons in suspension;
120,520,000 tons in solution.

The most important of the substances thus dissolved and transported are the carbonates of lime and magnesia, $CaCO_3$ and $MgCO_3$; the sulphates of lime, soda and potash, $CaSO_4$, Na_2SO_4, and K_2SO_4; chloride of sodium NaCl, and silica, SiO_2. In humid regions where there is much vegetation, the latter by its decay generates carbonic acid and by the aid of this the percolating waters dissolve lime and other carbonates from the rocks, as previously explained. Hence in humid regions the water of rivers, like the Potomac and the Dela-

* Metric ton = 1000 kilograms = 2204 pounds.

ware, have chiefly carbonates in solution; in arid regions where vegetation is sparse or wanting they contain mostly sulphates and chlorides, as in the Colorado and the Rio Grande.

Estimation of a River's Burden. — To ascertain the amount of material carried by a river its average annual discharge of water must be known, and the average amount of sediment in suspension and of salts in solution, in a measured volume, obtained. For the former the area of the average cross section and the average flow, in feet per second, must be known, by constantly repeated measurements, during every part of the year. The cross section multiplied by the flow gives the average discharge per second from which the yearly discharge can be obtained. In a similar manner repeated filtrations of unit volumes of the water will give the sediment in suspension, which can be weighed, while evaporation of the filtrate would yield the salts in solution, which can also be weighed. The composition of the salts can then be found by chemical analysis.

Many of the great rivers of the world have been more or less studied in this way, the Mississippi probably the most completely, and the following data obtained for this river are of interest and importance.

Average annual discharge 19,500,000,000,000 cubic feet.
Average annual amount in suspension 406,250,000 tons.
Average annual amount in solution 120,520,000 tons.
Average annual amount rolled on bottom 40,000,000 tons.
Total annual burden 566,770,000 tons.

Rate of Erosion. — It has been estimated that the above amount of material in suspension and rolled on the bottom discharged each

Fig. 30. — Burden of the Mississippi compared with the capitol at Washington. Prism one mile square, lower section material in suspension, upper, that in solution; total height 325 feet. Capitol on same scale.

year into the Gulf of Mexico, if gathered together, would form a right-angled prism with a base one mile square and a height of 268 feet. If the amount carried in solution is added the height of the prism would be approximately 325 feet, see Fig. 30, and if we reckon the whole basin of the Mississippi and its tributaries as covering 1,250,000 square miles it is then clear that this whole area is lowered by erosion at the rate of one foot in 3840 years. As the area in-

volved is so vast and concerns so many varieties of types of country, of rocks, soils, and climates we may fairly consider this as representing a general average for the whole world and thus say that the surface of the land is being lowered by erosion at an average rate of about one foot in 4000 years.

Other rivers, according to circumstances, have given different figures. Thus it has been calculated that the Ganges erodes its basin at the rate of one foot in about 1750 years. But its basin culminates against the loftiest mountains in the world and the river has a proportionately rapid descent and erosive power. The basin is also subject during part of the year to a very heavy rainfall and great floods. Thus the rate is far greater than the average. On the other hand desert regions, like those in Central Asia or the Sahara in Africa, with very little rainfall, erode with great slowness, the chief agent of transport being the wind. Between these, for the reasons stated, the Mississippi basin may be taken as a fair average. The average height of North America above the sea has been roughly estimated as about 2000 feet; at the rate given it would take 8,000,000 years to reduce it to sea-level, but as erosive processes (excepting solution) go on more and more slowly as the slope is reduced this time in reality would be, proportionately, enormously lengthened out.

Manner of Transport. — In considering the manner in which material is carried one must recall that it is only in swift streams and the upper rapid tributaries of great rivers that bowlders and coarse gravels are moved, especially in times of flood. As one goes down a great river the size of the material steadily grows less as the grade diminishes. This is seen, not only in the matter in suspension, but on the bars and beaches where it is temporarily deposited. Finally in those rivers which wander through wide plains before they reach the sea only the finest sands, silts, and clays are discharged into the ocean and no coarse material is seen, except in those accidental cases where pebbles and bowlders have been carried, attached to masses of river ice or entangled in the roots of trees, which float them down stream.

Nor is the journey a steady or uninterrupted one. The grade changes from place to place and with it the velocity and transporting power. Material carried down one reach is deposited at the foot of it, while at the head of the next rapid erosion is excavating the channel upward and material is again set in motion. Matter which is dropped at one time of year, when the current is slack, is seized and again hurried forward with the renewed strength that comes in times of flood. Thus, with many waits and pauses, and growing finer by attrition, the mass of material, upon which the river works, is being urged forward, more and more, and ever onward, down stream.

Graded River. — Since in those places where the grade is lessened a stream tends to deposit, while erosion again sets in when the grade increases, it follows that, as time goes on, a river proceeds to fill up the hollows and to cut away the projections in its bed and to thus establish a definite grade. The grade which the river seeks to establish is that at which, in each part of its course, the velocity is sufficient for the volume of water there present to transport its burden without erosion or deposition. This does not mean that the grade is necessarily a uniform one from source to sea; it may be relatively much steeper in the upper course, where the burden is of coarse detritus and the water volume small, than in the lower part where the slope is gentle but the water volume large and the load of fine sediment. A very heavily burdened stream, like the Platte, may become graded on a relatively steep slope, as compared with an underloaded one, which on such a slope would be still eroding. It is also clear from this the lower parts of rivers, especially of the great rivers, such as the Mississippi, become graded while, in the head waters, cutting and deepening by erosion is still actively going on.

River Valleys

River valleys are one of the most expressive features of the work of erosion by rain and running water and their characters are best seen in the upper courses of rivers where these agencies are most actively at work. The normal profile, or cross section of a valley, which is undergoing erosion is that of a V, as shown in the diagram, Fig. 31, because the river, occupying a relatively small space, is cutting downward in the center, while at the same time rain wash and gullying tend to broaden the trench, which the river makes, by washing down the material composing the valley walls. As already shown, as fast as this débris reaches the river, it is seized and carried away. The profile which the valley displays depends then on the relative balance between two agencies, the downcutting by the river and the broadening by general erosion. Thus in high or mountain regions, where the grades are very steep, downcutting by the river may exceed general erosion, the valleys are deeply incised and have profiles like *ara* in Fig. 31. As time goes on and the river grade is lessened the cutting by the river becomes slower and slower; general erosion then becomes relatively more and more pronounced

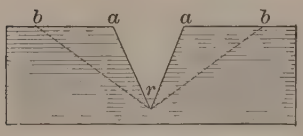


Fig. 31. — Section of a river valley; *a–b*, material removed by weathering and rain wash; river, *r*, trenching downward.

and the valley widens out as shown in *brb* of Fig. 31. A deeply incised valley, such as that shown in Fig. 32 where trenching by the river is the predominant feature, is called a *young* or *immature* valley; one in which river cutting has become very slow or has ceased and which is broadly opened by general erosion is termed a *mature* valley.

Fig. 32. — A valley in a youthful stage of its history. Yellowstone River. J. P. Iddings, U. S. Geol. Surv.

It should be clearly understood, in the use of these terms, *young* and *mature*, that absolute age is not at all referred to; that they are merely expressions to denote relative types of development of topographic form in a river valley during its history. A drainage system with valleys of the first kind, and with correspondingly accentuated ridges intervening between them, may be said to be a region with youthful topography; one with widely opened valleys and

subdued ridges and thus showing prolonged general erosion, may be said to possess a mature topography. But it is evident that a region composed of soft material and with abundant rainfall may arrive at a condition of topographic maturity while one with hard rocks and little rainfall, although originally of similar elevation and river grades, may be still in a condition of topographic youth.

Irregularities: Canyons and Gorges. — It is evident that in the balance between river deepening and erosional widening of a valley the nature of the material operated upon must be a prominent factor. Few rivers, if any, flow continuously through regions of homogeneous rocks of uniform resistance to erosion. But in the trenching of the river, by its strong grinding action, relative degrees of rock hardness may have but little effect, or none, while such differences may produce marked ones in valley widening which is due to the much milder agencies of weathering and rain wash. A mass of rock of a certain kind may yield readily to the former and resist sturdily the latter. Such variations in material produce irregularities in the general form of valleys, which rarely indeed possess the straight trough-like form we should in theory expect, but instead are winding with alternating spurs descending into them of the more resistant rocks passed through, see Fig. 33.

Fig. 33. — Course of a river valley with alternating spurs.

This is illustrated in the case of many streams flowing downward from the Rocky Mountains to the plains below. Where they pass through beds of soft, easily eroded shale-rock their valleys are open and smiling; where they enter hard resistant limestone strata the valley walls close into stern and rocky gorges or canyons.

The inability of weathering and rain wash in widening to keep pace with deepening by river trenching in resistant material is well illustrated by the Ausable Chasm in the Adirondacks, a gorge from 100 to 200 feet deep and from 20 to 40 feet wide, cut in hard sandstone. Still more striking examples are seen in the southern Appalachian Mountains; as in the gorge of the French Broad river in North Carolina, or that of the Tallulah river in Georgia which is nearly 1000 feet deep. Notable examples occur in California on the streams flowing from the Sierras and in many other parts of the world.

In arid regions the process of valley widening is obviously reduced to a minimum, while the main drainages, collecting such water as falls, are still subjected to stream trenching. Hence deep, narrow ravines, or coulées, gorges, or canyons, become natural features of topographic relief in such regions. In this case the nature of the rock masses operated upon becomes of far less moment, and valleys of the character mentioned occur in both hard and soft ones alike.

If the region is elevated these features become accentuated because of the greater trenching power of the streams, owing to the increased declivity. If the rivers rise in an area of greater rainfall and project themselves into one of aridity these effects become still more marked, owing to the increased volume of water. All of these

Fig. 34. — Grand Canyon of the Colorado river. View is mostly of the inner gorge; the wall of the upper broader canyon is seen in the distance. J. Hiller, U. S. Geol. Surv.

conditions are met in the rivers which drain the Plateau region of the Southwest, notably the Colorado river and its tributaries. Rising in the Rocky Mountains, where the precipitation is considerable, they flow out in strong volume into an elevated region whose descent affords steep grades, and whose arid climate renders valley widening

extremely slow. Thus we find the Colorado and its affluents flowing in the deepest and most magnificent set of canyons in the world, see Fig. 34.

Of all of these canyons the Grand Canyon in Arizona is the most stupendous, and one of the most impressive wonders of the world. It is over 200 miles long and from 3000–5000 feet deep and in width it averages about 10 miles. In general its profile shows a broader upper canyon within which lies a deeper inner gorge as illustrated in the ideal section shown in Fig. 35. It is cut in horizontal beds of rock of varying degrees of hardness. These rest on underlying granite

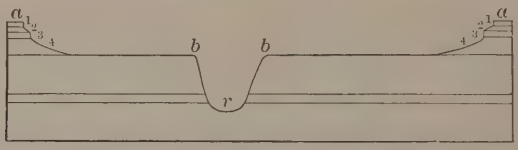


Fig. 35. — Ideal section across the Grand Canyon (after Dutton). *aa*, outer canyon walls; *bb*, inner gorge; 1 and 3, hard resistant beds; 2 and 4, soft beds.

which in one stretch has itself been cut into for a depth of 2000 feet in the inner gorge. The harder more resistant rock layers form cliffs whose talus slopes cover the softer beds. These effects and the irregular cutting, carving and recessing of the canyon walls through ravines and side valleys have given rise to enormous and striking architectural forms and appearances as illustrated in Fig. 34. Some of the masses thus carved out are themselves large mountains. The river is a swift, turbulent stream, turbid and laden with silt, from 200 to 300 feet wide and 2400 feet above sea-level opposite Bright Angel, the place in Arizona where the canyon is attained at present by the railroad and thus ordinarily seen. The Colorado must be considered as a young river in respect to the character of its valley, and having in view the magnitude of the task which it has yet to accomplish in deepening and widening the valley. In reality it is a rather old river but it has been rejuvenated and its period of youth, as well as the work it has to do, has been enormously increased through uprise of the land, a matter which will be considered later.

Fig. 36. — Section of the Rio Virgen, after G. K. Gilbert.

Relation to Tributaries. — Examination of drainage systems shows that in a vast majority of cases the tributaries of a river enter it at grade, at the same elevation as the main stream. They are thus said to be *accordant*. The reason for this is that as the main stream lowers by trenching the resulting increased declivity which is given the tributaries enables them to keep pace in spite of the smaller volume of water. But this may increase the ratio of the trenching

of the lateral valleys over their widening to a greater degree than in the main trunk valley and hence they may be proportionately narrower and steeper. An astonishing instance of this is afforded by the Rio Virgen, one of the tributaries of the Colorado river. In its haste to keep accordant relations with the main stream it has cut a canyon whose narrowest profile is shown in Fig. 36. In some cases however, small streams, unable to keep up with a rapidly down-cutting river, are obliged to cascade down the main valley walls.

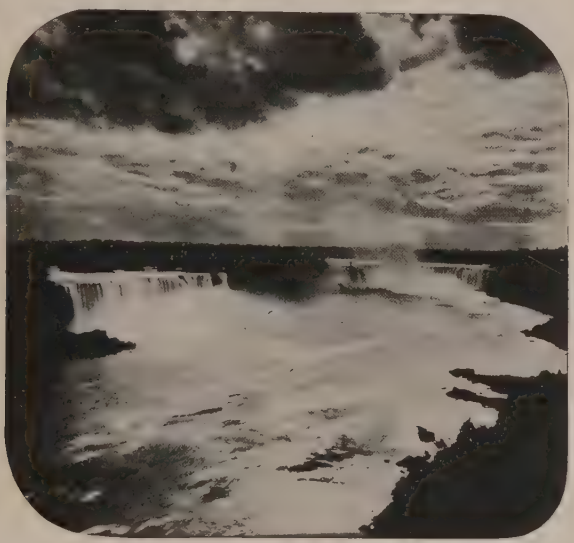


Fig. 37. General view of the Niagara Falls.

Waterfalls. — One striking feature frequently seen in valleys is waterfalls, the result of the unequal erosion of rock masses which differ in resistance. This is magnificently illustrated in the great cataract at Niagara which may thus be selected as an example for study. The Niagara river, which drains the four great upper lakes, in its course of 36 miles from Lake Erie runs over a plateau which terminates near Lake Ontario in an escarpment over 300 feet high. The plateau is capped by a hard resistant layer of rock known as the Niagara limestone, under which are soft easily eroded Niagara shales. Originally the falls was situated at Lewiston at the mouth of the river, and falling over the escarpment had its full height at this point. These relations are seen in Fig. 38. By the gradual disintegration and undermining of the softer underlying shale the harder limestone on top is left projecting as a lip, or table, over

which the water falls as shown in Fig. 39. From time to time the projecting table rock, left unsupported and penetrated by joint cracks, also falls and is carried away. By means of this arrangement and the more rapid wear of the underlying beds the falls maintains itself and is at the same time steadily moving upstream, leaving a deep gorge behind it until it is now 7 miles above its original position.

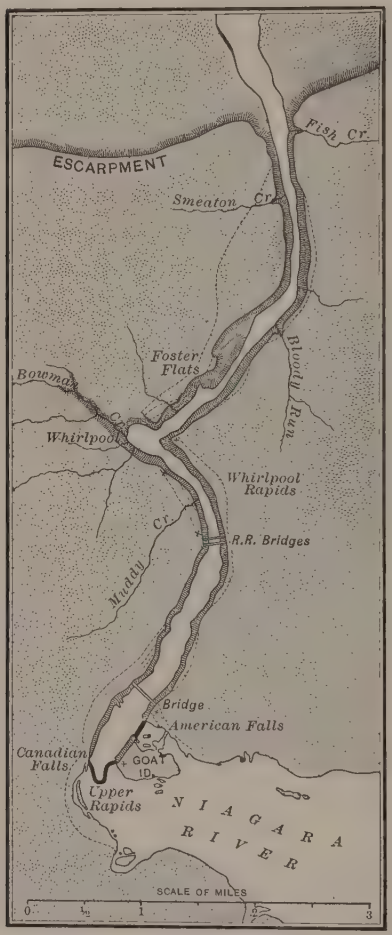


Fig. 38. Map of Niagara Falls and river, after G. K. Gilbert

The recession of Niagara Falls is a matter of interest and has been the subject of much study because it gives an idea of the length of time involved in geologic processes. At present the main, or Canadian, fall appears to be receding at a rate of about two feet a year, the American fall at a rate much less than half this. The face of the falls is now comparatively broad, about 4000 feet; when it was contracted in the narrow gorge below, its width was about one quarter of this and, owing to the greater concentrated weight of water, the rate of recession must have been more rapid. If we accept an average rate of five feet per annum, as has been assumed by some, the length of time involved in cutting the gorge (7 miles) would be 7000 years. This is a minimum estimate, but the problem is not so simple as this since many factors, involving various changes in the river and in the volume of its water which have occurred during the past, must be taken into account and some estimates which have done this run as high as 70,000 years. While we do not know the length of time with even an approach to accuracy these estimates are of value in that they show it is to be reckoned in tens of thousands of years, not in hundreds, nor in millions. The height of the falls, which is now about 160 feet, diminishes as they move because the layer of Niagara limestone which conditions them dips gently downward upstream.

Many other famous waterfalls are due to an arrangement of rocks similar to that at Niagara, such as the falls of St. Anthony on the upper Mississippi at Minneapolis, and its tributary streams, which fall into the gorge below; the Shoshone Falls on the Snake river in Idaho; those on the tributaries of the Columbia river, and smaller falls in New York state like Trenton Falls.

But falls may be produced in other ways as well, by glaciers, as will be noticed later, by the accidental damming of streams by lava flows or landslides, and, as Dana has shown, they are a natural result of the mature erosion of the headwaters of streams in mountain regions whose declivities become steepened by erosive processes.

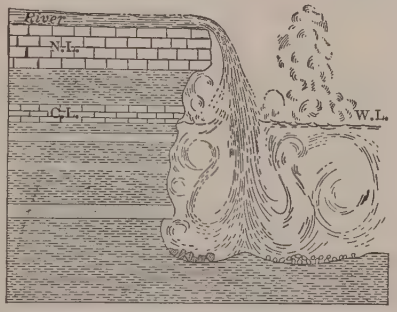


Fig. 39. — Section showing rock layers and cause of falls at Niagara. (After G. K. Gilbert.) N. L., Niagara limestone with soft shale below; C. L., Clinton limestone with shales and sandstones below. 300 ft. = 1 inch. W. L. = water level of pool.

It is clear that waterfalls, whether occasioned like Niagara by unequal hardness of rocks, or due to obstructions in the course of a stream, or to some previous geological action, cannot indefinitely persist; they must be worn away in time and disappear, for reasons previously stated under river grading. The more sediment a river carries, the less likely they are to be found in its course, or the shorter will be their life. Thus they are commonly regarded as signs of topographic youth in regions where they occur.

Pot-Holes. — A minor feature, seen in the bed of rapid, swirling streams, consists in the presence of pot-holes, Fig. 40. These are circular excavations worn in bed-rock by the whirling action of eddies. If the conformation of the stream bed is such that an eddy persists in one place the water whirls sand and gravel with it and this bores downward; although the material wears out in grinding it is continually replaced by fresh, and the process continues. Such pot-holes may have diameters from a few inches up to 50 feet, and the depth may vary to a similar extent, or be even greater. They are of interest in that they indicate so clearly the action of whirling water and, occurring not infrequently in country rock now far from any stream, they prove that at one time it was the bed of a rapid current.

Constructive Work of Rivers

So far in the study of rivers we have considered the destructive erosional work which they perform — work done chiefly in their upper reaches and seen in the valleys they excavate in the higher lands. Some rivers have a swift course through elevated tracts of country to the sea, their work is cut short when they enter it, and they deliver their burden at once; but many, and especially the largest rivers of the world, descend into wide lowlands, through which with

steady current they wind to their journey's end. In these lowlands, and at the river's mouth, the work done is different from that in the upper reaches; it is largely constructive, rather than destructive, and consists mainly in the deposition of the burden assumed through erosion in the higher part of the course.

Fig. 40. — Pot-holes worn in granite rock by stream action. Tuolumne river, Cal. U. S. Geol. Surv.

Flood Plains. — The lowlands situated on the lower courses of rivers are subject annually to floods caused by spring rains and the melting of snows in the mountains. Unless otherwise checked the river overflows its banks and spreads widely a vast volume of muddy water over these flat lands. The country may appear as a great lake for many miles outward from the course of the river. As the velocity of the water, except in the main channel, is checked in spreading outward it deposits its burden of fine mud and silt. Finally the waters recede leaving the deposit of mud behind. Such a deposit is known as *alluvium* and the flat lands along the lower courses of rivers, built up by these successive deposits, are often called *alluvial plains*. Rivers running through their alluvial plains, like the Mississippi, are generally in that phase of development or stage of their history, which has been previously explained as graded. The condition of the country through which they are passing will be considered later under the heading of base-level. For convenience

in description the whole flood plain may be divided into two parts, the river flats or swamps, and the delta.

River Flats and Swamps. — Examination of the alluvial plains along the lower courses of rivers shows that in general the land is somewhat higher next to the river and slopes away as one goes from it. The reason of this is that in times of flood, when the river overflows its banks, the overflowing muddy water having its velocity checked, as it leaves the main current of the river, at once commences to deposit, and the latter is therefore most abundant near the stream and composed of the coarsest material carried by it. The low ridges formed in this way are often called *natural levees.* Beyond these the land is low, more or less ill drained, and, in humid

Fig. 41. — Illustrates bars and deposits made by an aggrading stream in a flat part of its course. Junction of Cooper's river and the Yukon. W. C. Mendenhall, U. S. Geol. Surv.

regions, commonly covered with trees and other vegetation and thus of the nature of swamps. The river plain of the Mississippi is estimated to cover an area of 30,000 square miles and a large portion of it consists of extensive swamps.

While river flats and swamps are most natural and prominent in the lower reaches of streams, they may occur in any part of its course where a sudden lessening of its grade may cause it to deposit extensively, or *aggrade,* see Fig. 41. The stream would here build up a flat, gently inclined area through which it would wind with a steady current; beyond this it would again descend and regain its erosive power. Thus, while such flats are built up at the upper end, they are being carried away by rain and river work at the lower one. Ulti-

mately, as the river becomes graded, they must disappear and hence they are temporary lodgments of material, as contrasted with the final river-plain which must endure as long as the land is affected by the same set of geological conditions. In many cases these upper river flats represent lakes, or ponds, through which the stream passed and which have been filled up and obliterated by deposit. The same characters and river work, which are features of the great alluvial plains, may be seen in them on a smaller scale.

Deltas: Mode of Formation. — The lower river plain is frequently continued by an area of similar flat, low-lying land extending into the sea or lake into which the stream discharges. This tract usually has a triangular shape with one apex pointing upstream, from which fact it has received the name of delta, since it has a shape similar to the Greek letter so called. On reaching it the river usually splits into many branching streams which wander

Fig. 42. — Delta of the Nile, showing its form and distributaries.

through the delta in a roughly fan-shaped arrangement as illustrated in Fig. 42. These branches are called *distributaries*. The delta represents land which has been formed by the river and reclaimed from the sea or lake. While a considerable part of the burden of sediment carried by the river may be deposited, as we have seen, upon its alluvial plain another, and usually the larger portion, is carried on to the river's mouth. On meeting still water the current is checked and the sediment in suspension is deposited, while that

rolled on the bottom comes to rest. Through this continued deposition land is formed and the growing land pushes seaward. As the current of the river urges forward some distance into the body of water into which it discharges deposit takes place along the sides of this current, as well as at the point where it ceases, and this forms seaward a continuation of the natural levees. At the place where the current stops the heavier material is promptly dropped and this builds up a *bar*, or bars, across the mouth of the river. The rising bars may finally obstruct the course of the river to such an extent that it breaks through the natural levees at some point upstream and seeks an outlet elsewhere, leaving a diminished volume of water escaping by the old channel. The new outlet goes through the same process and thus, by upbuilding natural banks and bars and by

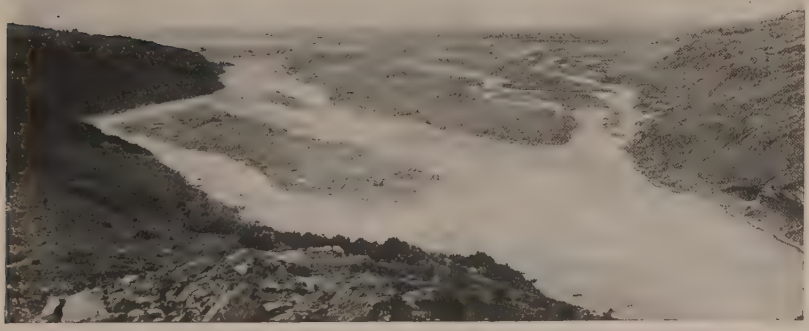


Fig. 43. — Delta of the Yahtse River, Alaska. I. C. Russell, U. S. Geol. Surv.

breaking through, the branching system of distributaries is formed and shape given to the delta. The branching system extending seaward, as illustrated in Fig. 43, represents the skeleton of the growing delta; between these arms lie very shallow basins which gradually fill up with finer material and thus become land, at first mud flats or swamps, and then more solid land as the annual overflows build it up by their deposits. The result is seen in Fig. 44.

Conditions Necessary for Deltas: Examples. — Deltas, especially those of great rivers, are commonly formed of very fine muds and silts; as the river descends into its plain, its velocity is diminished, the heavier and coarser material is dropped, the grade is further lessened by winding and only strength to carry the finer sediments

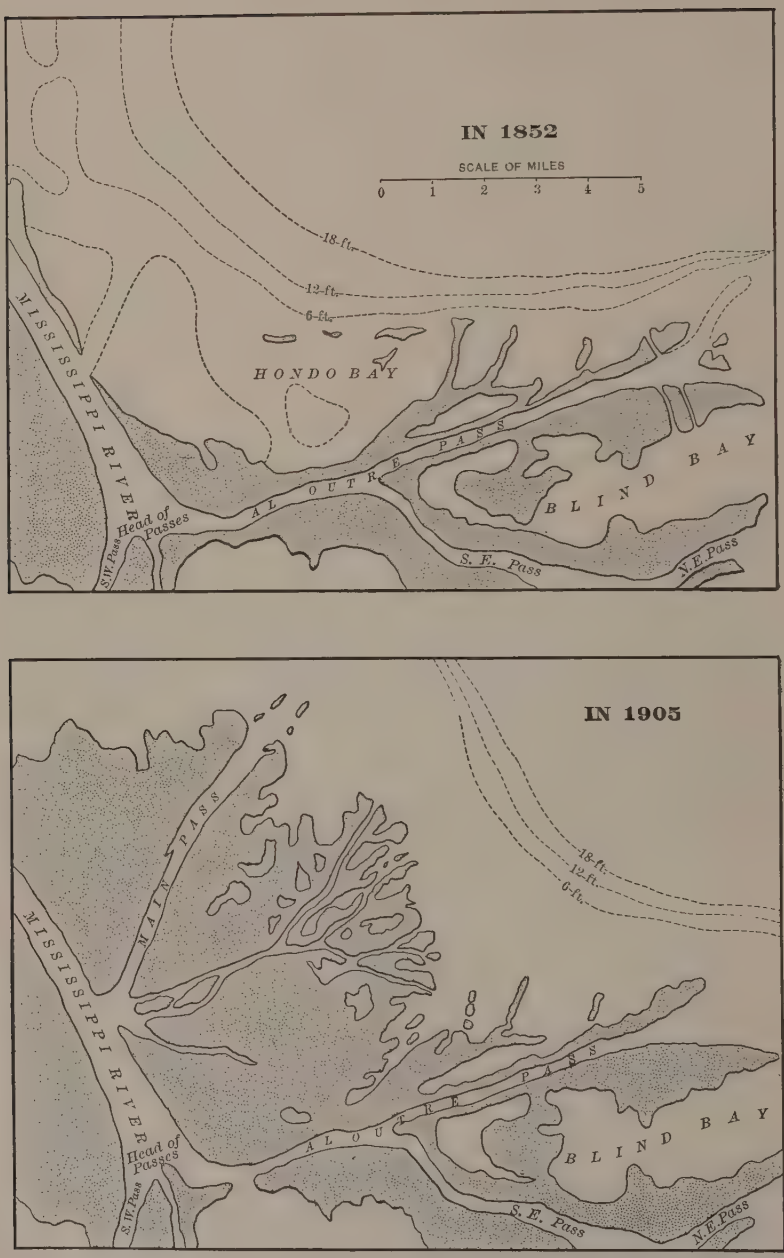


Fig. 44. — Illustrating the growth of the Mississippi delta during 50 years, after G. R. Putnam.

remains. It now becomes a question between the amount and coarseness of sediment which the river can discharge and the ability of the waves and currents in the body of water into which it enters, owing to their extent and strength, to sweep it away and prevent delta formation. Hence rivers entering lakes and enclosed seas, such as the Gulf of Mexico, the Black, Caspian, and Mediterranean seas, where waves and tidal currents are weak, form deltas. This is illustrated by the Mississippi, the Danube, the Volga and the Nile, all of which have deltas. It may also happen that, even in seas where there is considerable tide and rather strong currents, the conditions may be such, and the volume of sediment so large, that rivers can form deltas. This is illustrated by the Rhine, the Niger, the Ganges and the Hoangho rivers. The Thames on the other hand forms no delta because the strong tidal currents in the English Channel sweep the sediments away. On the Atlantic coast of North America there are no deltas because this portion of the continent in a very recent geological period has undergone considerable subsidence, such deltas as the rivers may have previously formed have been submerged, the ocean has entered the river valleys, flooding them and converting them into bays and estuaries; the rivers are now depositing at the heads of these estuaries seeking to fill them up and form new deltas. If the floor of the ocean is sinking, as appears to be commonly the case under very large deltas, it then becomes a question, between the rate of upbuilding by river deposit and that of the subsidence, whether the river can succeed in maintaining a land area of its delta, or not. It must also not be forgotten that in any case a considerable portion of the delta deposit on its seaward slope is under water. This extension consists of the finest material which is carried out some distance before being deposited, and it constitutes the submarine platform on which the landward area rises.

The deltas of great rivers form large areas of land, that of the Nile is nearly 100 miles long and 200 broad on its seaward front; that of the Ganges (and Brahmaputra) 200 miles long and its area possibly 40,000 square miles. The Mississippi delta is 200 miles long, its area over 12,000 square miles, and the thickness of the deposit over 800 feet. The great thickness is due to combined subsidence of the sea-floor and deposit by the river.

The ratio of growth of deltas depends on a variety of circumstances. The Mississippi has been estimated to be pushing forward into the Gulf at a rate of a mile in 16 years. This rate is probably more rapid than in former times for several reasons. The country drained by the river and its tributaries is now widely settled and cultivated and with occupancy of the land has come extensive destruction of forests and the upturning and exposure of the soil for agriculture. This produces a more rapid erosion of the basin and a larger vol-

ume of sediment. The flood plain is now mostly protected from the annual overflows by a great system of levees and this has transferred the sediment which would otherwise be deposited upon it to the extension of the delta.

Artificial Levees. — The control and management of large rivers in their flood plains is one of the most serious problems in engineering that civilization has to deal with. Alluvial plains and deltas are composed of fine, rich and fertile soil and hence are apt to be much cultivated and thickly populated. These lowlands are protected from the annual overflow by levees, as mentioned above, which raise the natural ones above the level of high water. In the Mississippi the increased volume of confined water by adding to the strength of the current has increased the scour and deepened the channel. The case of the Po and other rivers long leveed would appear to indicate that this can only be temporary, though, owing to the fineness of sediments, it may long continue. With increased current coarser material must be deposited further and further downstream and the river bed must gradually rise and, correspondingly, the levees must also be raised. This has been done on the lower Po to such an extent that the river bed and confining levees are stated to be above the tops of the houses in places on the lower plain. The accidental breaking of the levees entails wide flooding of the river plain and great disaster. This has occurred a number of times on the Mississippi and notably on the Hoangho river in China, entailing in the latter case enormous loss of life.

The obstructions to navigation caused by the bars at the mouths of great rivers have, in the case of the Mississippi, been successfully removed by the building of crib-works, called *jetties*, in such a way as to prolong the natural levees out in shallow water, and to thus continue the current of the stream, so that the load of sediment is deposited in deep water instead of on the shallow submarine top of the delta, while the increased scour deepens the channel.

Alluvial Cones or Fans. — When a swift tributary stream enters into the wider and more level valley of a larger river the sudden change of grade may cause it to deposit the greater part of its burden on the floor of this valley. In this way semi-cones, or fan-shaped elevations, of deposits are formed. They may be regarded as deltas formed on land, but differ from true deltas made in water by their shape and, generally, by the coarser material composing them. A view of such an alluvial cone is seen in Fig. 45. They are often conspicuous in the broader valleys in arid districts where material is washed out of the narrower tributary ravines by sudden heavy downpours of rain and deposited. In these regions whole basins may be filled by such rain wash deposits and present very level floors.

Meanders. — A river, either in its upper flats or in its ultimate flood-plain, has a relatively gentle flow owing to the low grade and in consequence a diminished strength of current. It is therefore easily turned by obstacles and tends to wander in the plain in a series of winding curves called *meanders*. Nor does it long maintain a set course but shifts about by changing its course and forming

Fig. 45. — Alluvial cone, made by a tributary to a larger stream. Stoughton, Wis. W. C. Alden, U. S. Geol. Surv.

Fig. 46. — Meanders of a stream in a nearly flat region. Trout creek, Yellowstone Park. C. D. Walcott, U. S. Geol. Surv.

new curves. Even if artificially straightened it would soon begin to wander. The reason for this is as follows: The swiftest part of a river current is normally in the middle of the stream; if it encounter any obstacle, such as a rock or stump, it is deflected against the opposite bank. The latter will be eroded and this will tend to throw the current against the opposite bank (as in *A*, Figs. 47 and 48) which will in its turn be eroded. Thus meanders begin to form

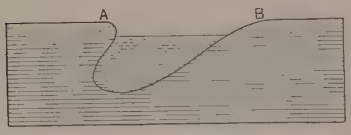


Fig. 47. — Section of a stream channel from *A* to *B* shows it to have the profile seen above, the deepest part lying close in to the hollow bank at *A*. See Fig. 48, *A* and *B* the same.

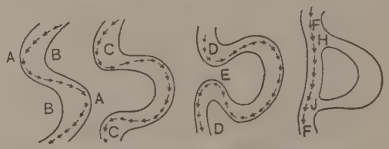


Fig. 48. — Illustrating the formation of meanders and ox-bows.

and a continuation of the process increases them. Meanwhile the current being slackened at *B*, Fig. 48, deposit takes place there and the point grows out as the hollow recedes. Further stages of the process are shown in *C* and *D*. Eventually in the process of meandering, a loop, as at *E*, is cut through leaving an island in the river, the main current takes the shortest route *FF* and the entrances to the abandoned channel *HJ* become silted up leaving a shallow crescentic lake. Such lakes are called ox-bows, or *bayous* on the Mississippi; they gradually fill up and become sloughs or marshes, and finally perhaps low meadows, though retaining the original form by which their former character may be recognized. Such old abandoned channels are very common on river flats and plains.

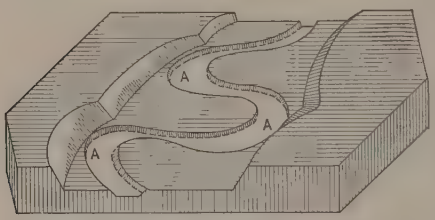


Fig. 49. — A river widening its valley by meandering and planation.

Work on River Plain; Planation. — If a river is graded either temporarily upon an upper flat or on its plain it neither lowers its channel by cutting down (corrasion) nor builds it up by deposit (aggrading). In this case, as it wanders by meandering at the same level from side to side in its valley, it impinges against the valley bluffs from time to time, as at *A* in Fig. 49, cuts them down by undermining and carries the material away. By continuation of this process the valley is widened and this work is known as *lateral planation*.

There appears to be some relation between the size of a stream and the width of the valley it is able to cut by this process. A recent estimate places the valley width at 18 times that of the average width of the stream. An interesting feature which sometimes occurs in the process of meandering is the formation of natural bridges and arches. The mode of their formation is sufficiently explained by the diagram, Fig. 50. This is by no means the only way in which natural bridges are made; other methods are described later.

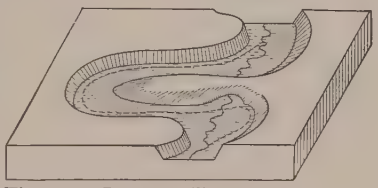


Fig. 50. — Diagram illustrating how the narrowing of the neck of a meander, combined with under-cutting and solution, may form a natural bridge. Dotted line shows former stream course. See Frontispiece.

Terraces. — There frequently occur in river valleys long narrow stretches of very flat and nearly level land, often on both sides of the river. Back of them on the side away from the stream may rise the ascending slopes of the valley, next to the river they may descend to the present river plain steeply or even in bold bluffs.

Fig. 51. — Terraces on the Fraser river, opposite Lillooet, British Columbia. A. M. Bateman, Geol. Surv. of Canada.

Often there are several of them raised one above the other like steps, or shelves. These are known as *terraces;* they are composed of alluvium, of river-deposited sands, gravels, etc., and they are the remnants of former river-plains, when the beds of the streams were at their altitude. They are illustrated in Fig. 51. They may be formed in a variety of ways, one of the most important of which is as follows: A stream may at one time in its earlier history be heavily burdened with sediment and deposit this at points of lessened grade,

forming river flats and an ultimate flood-plain. At a later time with decreased load and therefore renewed energy, it may begin eroding, cut into these deposits, start a new flood-plain, or flat, at a lower level, and thus leave the remnants of the former plain, or flat, as terraces, as shown in Fig. 52. Changes in the amount of water discharged in different periods might cause a similar result. On an upper river flat the increased gradient at the lower end, normally

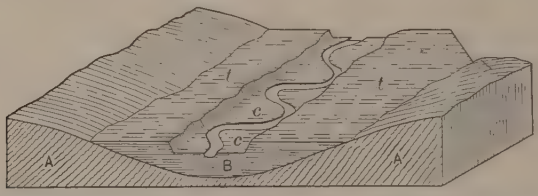


Fig. 52. — Illustrating formation of terraces. *AA*, Section of river cut valley; *B*, alluvial deposits of river; *tt*, former flood-plain, now forming terraces; *c*, new flood plain.

working upstream and deepening the channel, may leave remains of the former flat as terraces. Other agencies contributing to their formation will be described later. Owing to their low grades and situations in river valleys they have been extensively used in the location of railway lines.

Structure of River Deposits. Stratification. — Before leaving the constructive geological work done by rivers, it should be stated that all deposits by them, as indeed by all currents of water, whether rivers on the land or tidal currents in the sea, are so laid down, through the sorting activity of water, that they consist of distinct layers, or beds, of varying degrees of fineness. Usually these beds are very regularly parallel for greater or lesser distances, and deposits which exhibit this laminated, banded, or bedded appearance are said to be *stratified*, and the arrangement is called *stratification*. Whether on river flats, on alluvial plains, or in the delta, river deposits are thus stratified. This subject, and the importance of its bearing in understanding the origin of a great class of rocks, will be discussed in detail later, under the structural side of Geology.

Life History of Rivers

Study of the land surfaces of the earth has shown us that they are not permanent geological features. The expression "the everlasting hills" often used in literature has value only in reference to the duration of human life; geologically it has no significance. For not only are the lands subject to change through erosion, as we have

seen in the preceding pages, but they suffer changes of level, with reference to the sea, through raising or sinking of the earth's crust. This has often occurred in the past, and to such an extent that sea-bottoms have become land, or land surfaces have sunk to become sea-bottoms. Not only has this happened in the past, but it is occurring now, though so slowly that only one trained in geology is able to perceive it. The land surfaces also have been profoundly modified at times by warpings, by being covered with huge areas of ice, and in other ways. We need not stop to treat these matters here, since we shall study them in detail in appropriate places, except to understand that great changes of land level have occurred, and to consider its effect upon the life history of rivers.

Since, therefore, new lands have appeared from time to time, or old ones have had new levels and surfaces given them, it is evident that new drainages have also been initiated. For a long time such drainages have the characteristics of topographic *youth;* the upper valleys are narrow and V-shaped, the ridges between are wide and often flat; there may be lakes not yet filled up, waterfalls not yet eroded away, and similar features. As time goes on these are obliterated, the land is everywhere carved into drainage slopes, the main valleys are widened, the hill slopes become gentle and rounded, the rivers meander on their valley floors, they become graded, with harmonious relation between erosion and transportation; in other words they are *mature.* Only, as previously stated on page 47, these are relative terms, not ones of absolute time. We may now consider further stages of river history and land erosion.

Peneplain: Base-level. — If erosion were to continue unchecked upon a land area its surface would eventually be reduced nearly to sea-level; all projecting parts would be cut away, the material deposited in the sea and a plain left as the result. Since the work of erosion progresses in ratio more and more slowly as the heights and slopes decrease it is evident that the length of time required to accomplish this would be enormously, almost indefinitely, lengthened out toward the latter end of the process. Long before this could happen the land surface, especially the portion marginal to the sea, would be cut down to a low, almost featureless country of small topographic relief. In this stage of general erosion it is known as a *peneplain* (almost a plain, see Fig. 55), and the process is often referred to as *peneplanation.*

Finally, in a further stage the land would be reduced almost to sea-level; it would be practically flat with a grade so low that it would be just sufficient to give enough energy to shed the rainfall

seaward; erosion and deposition would have therefore ceased. The drainage is in consequence everywhere on the land surface thoroughly graded; and since there can be no features of topographic relief there are no particular channels, and the waters must drain as from a very flat roof. A land in this condition is said to have reached *base-level* and base-level is the theoretical goal at which erosion aims in its work, even if, so far as we know, no land surface has ever in reality been completely base-leveled.

Some writers have considered the sea-level as the ultimate base-level, but it is evident from the foregoing pages that erosion alone could never reduce a land absolutely to this level; enough of a slope must remain to carry off the drainage. Nor is the sea-level itself a constant quantity since it varies with the tides and has varied in the past for other reasons as well.

Upper flats and plains upon which streams meander and through whose extent they are graded are often spoken of as *temporary base-levels*. For practical purposes the lower alluvial plain of a river, like that of the Mississippi, in which it is graded, may be considered to be at base-level.

Fig. 53. — Drowned river mouth forming an estuary. Balaklava, Crimea, Russia.

Drowned and Revived Rivers. — If a land surface should be lowered sufficiently by subsidence the lower valleys of rivers would be flooded by the sea and would become estuaries, like Delaware and Chesapeake Bays. In this case the river is said to be *drowned.* See Fig. 53. The tributary rivers which formerly ran into the main stream are called *dismembered.* These relations are illustrated in

Fig. 54. If a river were carried below base-level by drowning it would begin to fill up the estuary by depositing and this work would go on until the whole bay is filled up and converted into a river-plain, which in a sense may be regarded as its delta. This is the condition of the rivers and estuaries along the Atlantic coast; in which the remaking of the drowned river-plain is only partly completed as shown in Fig. 54.

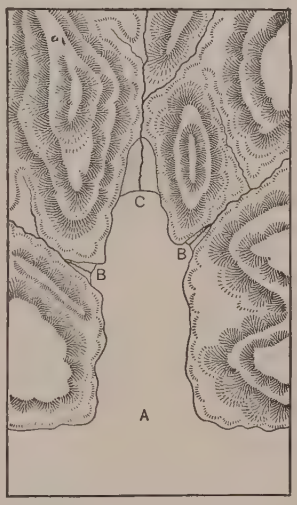


Fig. 54. — Drowned and dismembered rivers. *A*, estuary, drowned river; *B*, dismembered tributaries; *C*, remade alluvial land.

On the other hand, if a land surface should be raised, then the stream and its tributaries, in virtue of the increased gradient, would begin to cut actively and corrade their channels. Features of former mature topography may still be recognized, yet now through the uplift we find the river exhibiting the characters of youth. When this has happened a river is said to be *revived*. Thus the streams of southern New England, which is an upraised former peneplain, have again been set at work and are now excavating their valleys. See Fig. 55.

Terraces of Revived Rivers. — In the valleys of revived rivers it is common to find terraces, similar to those described on page 63;

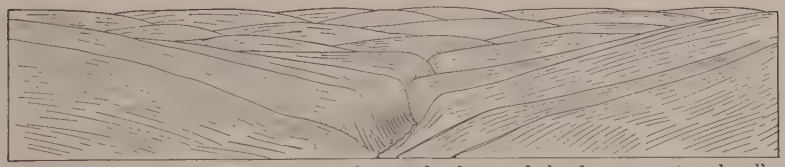


Fig. 55. — A revived river. Above, the gentle slopes of the former matured valley; below, the new trench of the revived stream. In the distance the accordant heights of the gently modulated topography show the level of a former peneplain.

but of greater height and more conspicuous. The mode of formation that is usually attributed to them is of interest and importance in

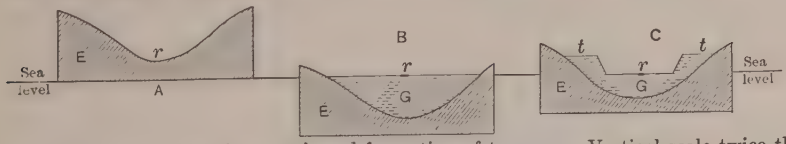


Fig. 56. — Illustrating river-work and formation of terraces. Vertical scale twice the horizontal.

that it involves both depression and elevation of land and may be described as follows, with reference to the diagrams in Fig. 56.

We first imagine a river r to cut out a valley in the underlying rocks E, as shown in section in A, the land standing at a definite level. If the land is now depressed so that the sea enters the valley it will be drowned and the river will deposit in the endeavor to raise its bed to base-level. When this has been done the section will appear as in B, the thickness of the deposit G indicating the amount of subsidence. If the land is now raised to a new level, as in C, the grade is increased and the revived river will again cut down to a new base-level which we may consider to be at r. It will then widen its valley by meandering and lateral planation, as previously described, and while this is going on the remains of the old flood-plain *tt*, usually fronting on the new one below with more or less steep bluffs, will form *terraces*. The height of the bluffs in a general way shows the amount of upraise.

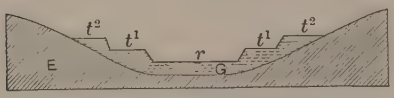


Fig. 57. — Successive uplifts causing terraces at different levels.

If the elevation has not taken place in one stage but by intervals with successive pauses, this may be also shown by the terraces; thus in Fig. 57 a first stage of elevation occurred and then during a pause the upper set of terraces t^2 were formed, then a second elevation and the inner river plain r was cut and is now widening with terraces t^1.

This explanation is the one generally accepted to explain the terraced aspect of the valleys of eastern North America but the other processes by which terraces are formed have probably acted in conjunction with it. Terraces cut in rock may also be seen in the valleys of revived rivers which mark pauses in the period of uplift. If a pause occurs the river will widen its valley, a new uplift will start it at its work of downcutting again and remnants of the older valley-floor of rock will be left as terraces.

Consequent and Subsequent Rivers. — If one imagines for any reason a new land surface, as for instance an upraised sea-bottom, then the course of the drainages on the new land would be determined by its natural slopes and topography. Rivers originating in this way are called *consequent* rivers because their courses are consequent upon such original relief features. They may persist in a region long after its original topography has been greatly changed by erosive processes having cut away the less resistant areas of rocks more rapidly than the harder, stronger ones.

On the other hand, as time goes on new drainage channels may appear, not dependent on the original topography, but determined by erosion acting differently on underlying rock areas according to their resistance, structure, etc., as illustrated in Figs. 58 and 59.

Rivers formed in this way are called *subsequent*. While some of the large rivers which drain the Appalachian region, such as the Delaware and the Potomac, are persistent consequent ones and are thus master streams, their affluents, whose valleys have been etched out along belts of weaker rocks, are largely subsequent.

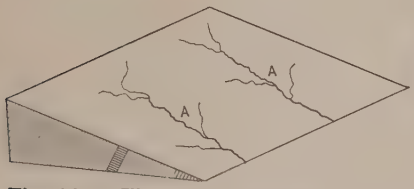


Fig. 58. — Illustrates consequent rivers *AA* on a natural slope, newly exposed; underground structure not yet revealed.

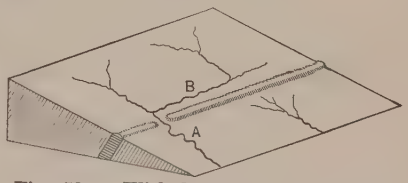


Fig. 59. — With lowering of surface by erosion in Fig. 58, a hard ridge of rock etches out; one consequent river, *A*, persists and becomes a master stream; the other drainage was diverted and forms a subsequent river *B*.

Antecedent Rivers. — During the long life of a river it may happen that an upwarping of the land may take place athwart its course. If the river has energy, and is cutting sufficiently fast, it may be able to saw down its channel through the rising upwarp and maintain its course. A stream, whose course has been thus determined by a previous topography and does not now conform to the present relief of the land, is called an *antecedent* river. Thus the Columbia is held to have cut its gorge across the mountains which try to bar its way, and the Kanawha in its course across an upraised plateau has preserved its original winding way. Similar instances are thought to occur in other parts of the world, as with some of the rivers of the Alps. In each case the river is thought to be older than the elevations; otherwise we could scarcely understand how such drainage ways could occur.

Superimposed Rivers. — It sometimes happens that consequent rivers have had their courses determined by natural features of relief on a new land surface consisting of materials of a certain kind. The courses thus determined may be persisted in by the streams, although, as erosion progresses and they continue to sink their channels, they may be compelled to do so in rocks and rock structures of a very different nature from those at the surface. Finally, erosion may strip off the overlying material entirely and with the topography etched out from the underlying rocks the old stream channels may appear as quite inharmonious. This is illustrated in Fig. 60. A river, whose course has been thus predetermined and which is not

now in adjustment with the general topography and rock structures, is called *superimposed.*

In this case its smaller tributaries are mostly subsequent streams. Care should be taken not to confuse antecedent and superimposed rivers. Both may

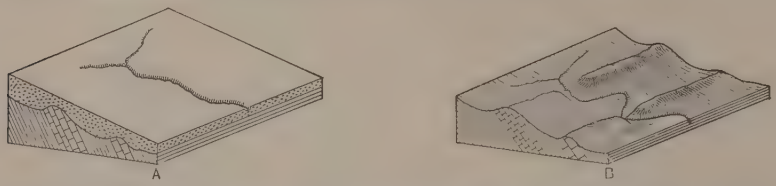


Fig. 60. — Illustrating the origin of a superimposed river, *A*, course determined by natural slope on a layer of sand and gravel; *B*, latter removed by erosion and river pursuing its course without regard to underlying rock structure.

cut gorges through elevations which lie as barriers athwart their courses, but in the former the elevation has risen through interior forces during the life of the river, while in the latter it has been produced in the general lowering of the surface by erosion, through some rock masses being more resistant than others, that is, by differential erosion.

The smoother the underlying rock surface is, the thinner the overlying mantle of material may be, to produce this result. If a surface of rocks of varying kinds of hardness and resistance were planed down quite level (base-leveled) and then elevated, the drainage would be rejuvenated and consequent; some master streams would persist in their courses and, although their tributaries through differential erosion would be subsequent (page 68), they would have the characters of superimposed streams, even if a mantle of overlying material may have been practically absent at the time of uplift.

The master streams of the Appalachian region, such as the Delaware, Susquehanna and Potomac, have the characters of superimposed rivers. This is well illustrated on the Delaware in the fine gorge it has cut through the Kittatinny or Blue Mountains, a barrier which erosion has etched out across its way.

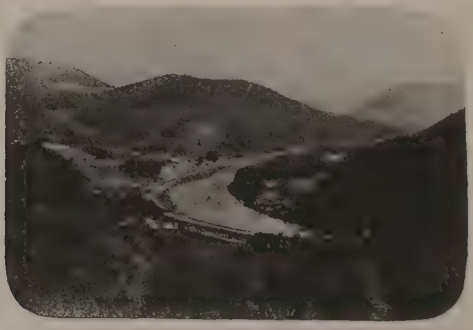


Fig. 61. — Entrenched meanders of the Deerfield river, Mass.

Entrenched Meanders. — A river whose course has been superimposed upon an old land surface by uplift, as described in the preceding section, very commonly has a winding course, its former

meanders on the plain having been sunk into the country. In this case they are said to be *entrenched*. This is illustrated in Fig. 61. Entrenched meandering courses of this kind are shown by the rivers of New England, of the Appalachian region, of Belgium, and of northwestern France.

Summary of River Work. — From what has been stated in the preceding pages we see that rivers have a double function; they both erode and transport. The work of erosion is chiefly done in the upper steeper parts of their courses; lower down, on their plains and at their mouths, the work is largely one of deposit and therefore constructional. Their greatest work is the transporting of the material furnished them by general erosion. Finally, we have seen that they have a life history which passes from youth into maturity, and on into old age, and that this life history may be lengthened by rejuvenation. Other features of stream work, such as the nature of their deposits and the ways in which they may modify the relief features of the land, will be treated later.

CHAPTER III

LAKES AND INTERIOR DRAINAGES

Lakes are enclosed bodies of water, either still, or with but a gentle current; they are usually of fresh water, but many lakes, and some very large ones, are saline. Fresh water lakes have an outlet and in some ways may be considered as expansions of streams. While lakes are found in all parts of the world they are more common in northern and in mountainous regions; the reason for this is explained under glaciers. Lakes are caused by obstructions to drainage and such obstructions, or lake basins, may be formed in a great variety of ways, some of the more important of which are as follows:

Origin of Lake Basins. — (*a*) Depressions caused either by warping of the earth's crust, or by its breakage and displacement in huge blocks. The first is supposed to be the main cause of the Great Lakes, while to the second is due, in part at least, the basins of the large lakes in central Africa. Some smaller lakes in the western United States, such as Abert Lake in Oregon, have been formed by such displacements of the earth's crust. The warping of river valleys may produce lakes, such as Lake Geneva or Lake Temiskaming in Ontario. The largest lakes in the world mostly belong in this general class.

(*b*) Rock-basins which have been excavated by some means. The most common agency for these is the action of glaciers, as will be explained later; such glacial lakes are found in northern regions, and especially in high mountains; frequently they are inconsiderable in size. Some lakes which fill crater-pits due to volcanic action, like those in central Italy, also belong in this class.

(*c*) Lakes due to natural dams which have been formed across the drainage channels of streams. Such dams may have resulted from various agencies; they may be made by streams of lava, by accumulations of volcanic ashes, or by land-slides, to suggest examples. Most commonly, however, they are made of loose material such as sand and clay deposited by streams, or earth and stones left by the moving ice of glaciers. Thus a swift tributary may deposit more, and coarser, material in a slowly moving main river than the latter

can carry, whereupon a dam will be formed, and the larger stream expanded into a lake above this point, as the Mississippi is changed into Lake Pepin by the dam made by the Chippewa river. Where streams enter the sea through estuaries, the ocean waves may throw up barrier dams across their mouths converting them into a fresh water lake. Examples of this are numerous along the Atlantic coast. Perhaps the larger number of lakes, which spangle the surface of the northern part of the country and lend charm to the scenery of New England, the Adirondacks, Minnesota and Canada, are due to dams in valleys left by glaciers. The way in which these dams are made by waves and by glaciers is considered in detail in other places.

Relic Lakes. — Some lakes were once arms of the sea which have been cut off from it by natural dams formed by an upraise of the land, or by material deposited by some agency, such as the delta of a river. Subsequently, the rivers running into them have rinsed the salt out and they have become fresh-water lakes. Lake Champlain is an example of this. Such bodies of water have been recently named *relic lakes* and their former connection with the ocean is shown by the marine forms of life still living in them, often greatly modified in structure and habits by the changed conditions.

Functions of Lakes. — Several important geological functions are performed by lakes: they regulate the flow of streams with which they are connected and, by acting as storage reservoirs, prevent disastrous floods; if large, they tend to equalize the temperature of the country surrounding them, cooling the air in summer and warming it in winter. But the most important geological function they perform is in acting as settling basins for the sediment of river waters. In this way great accumulations of transported material are made and river waters are clarified. This is strikingly illustrated in Lake Geneva in Switzerland, into the upper end of which the Rhone pours as a thickly turbid stream, while from the lower end, at the city of Geneva, it issues as a river of beautifully clear blue water. Its deposited sediments have made a delta six to seven miles long at the upper end of the lake.

In lakes, especially the larger ones, may be seen the geological work of waves and of currents along shores. These are best studied, however, in connection with the seacoast where they are much more strikingly displayed.

The Life of Lakes. — Considered from the geological standpoint lakes are, in general, only temporary affairs. They are short lived, since, for reasons previously mentioned, the rivers which maintain them must in time fill them up with sediment, convert them into

river flats or alluvial plains, and thus obliterate them. And also, since the river gradient has a sharper slope where it leaves the lake, the channel must deepen and wear backward upstream faster at this point, and this may cut through the barrier and drain the lake before it is filled. Both filling and draining may coöperate to destroy the lake, but since, in general, water leaving a lake is clear and has little power to erode, filling must be the chief factor. This filling, however, in humid regions may be done quite as much or more by deposits of organic life as by transported sediments, as will be shown later.

Yellowstone Lake was once of greater size, and drained south and west into Snake river and the Pacific. The present Yellowstone river, then a much smaller stream but working rapidly backward on a steep grade, tapped the lake, partly drained it, and continues to divert its waters into the Missouri and so into the Atlantic.

Lakes, therefore, are considered to be indicative of topographic youth and, in general, this is true. Thus Florida, which is a sea-bottom raised in a recent geological period, still contains many shallow lakes on its very flat, slightly irregular surface, while the other Southern States, which are geologically old and have a mature topography, are destitute of lakes, save those made by the Mississippi and its tributaries in wandering on its flood-plains. The many lakes in the Northern States and in Canada are also the result of a new surface given the land during the recent ice age.

There are exceptions to this general rule that lakes are short lived and therefore recent. The great size of some lakes, such as those forming the group of the Great Lakes, often combined with special geological events, as in the case of Great Salt Lake, may serve to prolong the lives of some past the period when we should normally have expected them to disappear.

But while lakes must eventually be obliterated by filling, or draining, or both, there is a considerable difference in their final history, and also in their nature, dependent on the climate of the region in which they are situated and this demands consideration.

Lakes in Humid Regions. — In those places where the rainfall exceeds the amount evaporated from the surface of standing water annually, all depressions will fill up and become lakes, provided there is no underground drainage. Such lakes must have an outlet, and will overflow, and therefore, through change in the water, will remain fresh. And, while normally they must disappear through filling with sediments, as they become shallow, or if they were originally small, the process is greatly hastened by accumulation of black

carbonaceous matter called peat, resulting from the decay of various forms of plant life, and through this peat they become converted into marshes, bogs and swamps as the final stage of destruction. This process and other details regarding swamps are described in the chapter devoted to organic agencies.

Fig. 62. — A playa, or temporary lake, in a dry region. Wyoming. G. I. Adams, U. S. Geol. Surv.

Lakes in Arid Regions; Inland Drainage. — The amount of rainfall received by any region is dependent on the nature of the prevailing winds and on the topography of the country. In all continents there are areas which receive so little moisture that they are arid, or even desert, in character. Thus in North America the country lying between the Sierras and the Wahsatch Range, and mainly in Utah and Nevada, which is known as the Great Basin, has a very light rainfall because the prevailing winds coming from the west and the Pacific have most of their moisture discharged by the mountain ranges of California and Oregon before reaching it. In such regions the evaporation may greatly exceed the rainfall; springs are rare, streams infrequent and of scanty volume in respect to the size of the valleys which they drain; many depressions in these districts, which in humid climates would form permanent lakes, are dry, or only occasionally filled in times of storms and are then known as *playas*, see Fig. 62.

Surrounding such regions are stretches of country, often mountainous, which receive a greater rainfall and whose streams in part are directed into these arid tracts. On reaching depressions they fill them in part and form lakes whose size is dependent on a nicely balanced adjustment between the amount of water received from the river and that lost by evaporation from the surface of the lake.

Should the depression be small the river may fill it and pass on, but, as is very frequently the case, the amount evaporated may equal the inflow and the drainage system will then end in the lake. Such lakes vary in size during different parts of the year, or from one period of years to another, in response to fluctuations in the rainfall and the water discharged into them by the incoming streams. It may also happen that a river running into such a region may dwindle so much from evaporation, before reaching a depression suitable for the formation of a lake, as to entirely disappear. River systems like these, which end through evaporation in interior basins without reaching the sea, are termed *interior drainages*.

Fig. 63. — Alkaline salt lake near Parma, Colo. C. E. Siebenthal, U. S. Geol. Surv.

Salt Lakes. — It has been already explained in the description of the river's burden that a part of it consists of various salts in solution and that such salts are carried by all streams, even if, in a given volume, the water appears so fresh that they can only be detected by chemical means. In ordinary rivers these salts are discharged into the sea, but in interior drainages, since they cannot be dissipated by evaporation like the water, they must constantly accumulate at the point where the drainage ends.

If the river ends by dwindling, its lower part finishes in a stretch covered with salt deposits, sometimes in wet seasons converted into a salt marsh or shallow salt lake, and known as a *salina*. Examples of these are found in the Tarim river which ends in the desert of Gobi in central Asia, in the Desaguedero river which carries the drainage from Lake Titicaca in Bolivia, and in many other places. But if the end of the drainage system is a lake the latter is bound in time to become salt through the concentration of these substances, and such salt lakes are features of arid or desert regions in all the continents. Examples of them are the Dead Sea in Palestine, Lakes

Fig. 64. — Alkali deposit on the shore of Soda Lake, Parma, Colo. C. E. Siebenthal, U. S. Geol. Surv.

Baikal, Balkash and the Aral Sea in Siberia, Lakes Shirwa and Rudolph in Africa, Lakes Eyre and Torrens in Australia, and Lake Chiquita in South America. In North America the best ones are found in Great Salt Lake in Utah, Pyramid Lake and others in Nevada, and Mono Lake in California.

It is only the final lake in an interior drainage system which becomes salt; an intermediate lake remains fresh because its waters are changed. Thus Utah Lake which flows into Great Salt Lake, Lake Tahoe which runs into Pyramid Lake, and the Sea of Galilee which discharges into the Dead Sea are all fresh, while the terminal in each case is salt.

Great Salt Lake has an area of about 2000 square miles; its average depth is about 20 feet. The water is a strong brine, being five or six times as salt as that of the ocean, which in composition it closely resembles; its salinity is about 18 per cent, and the buoyancy, from the increased specific gravity, is so much higher than ordinary fresh water that one floats upon it almost like a cork. The chief salts are common salt (sodium chloride) and sodium sulphate; of the former

Gilbert estimated the lake to contain 400,000,000 tons, of the latter 30,000,000 tons. Calcium carbonate, which is brought in by the inflowing waters is deposited as a granular sand on the bottom and shores.

The waters of Great Salt Lake have receded in recent times owing to the diversion of the Jordan and Bear rivers, which maintain it, for purposes of irrigation, and the consequent evaporation of a part of the supply on land. In the last few years, however, it appears to be again expanding, owing, possibly, to an increase in rainfall and diminished evaporation.

Salt and Alkaline Lakes. — In Great Salt Lake, like many others of its type, chlorides and sulphates are the chief salts, but in some lakes, as in Pyramid Lake in Nevada and its neighbors, there are in addition notable quantities of the carbonates of soda and lime, and their waters give an alkaline reaction.

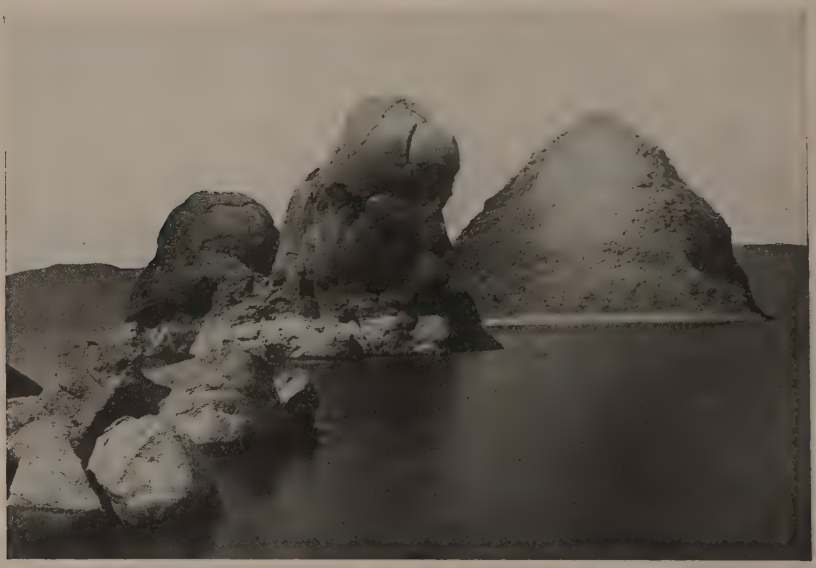


Fig. 65. — Islands of calcareous tufa in Pyramid Lake, Nevada. I. C. Russell, U. S. Geol. Surv.

We may therefore distinguish between these cases and speak of salt and alkaline lakes, although in western America all natural salts, either as deposits on the land, or in water, are commonly and incorrectly spoken of as "alkali," see Fig. 64. The reason for this difference appears to be that the water of Great Salt Lake drains from an area chiefly occupied by rocks that were once laid down as sediments on the sea floor; on being raised to form land they brought up in their pores the sea salts which are now being leached out, while the Nevada basin is largely covered by igneous rocks, lavas, etc., destitute of sea salts and largely composed of feldspar, whose decay yields carbonates as explained under the formation of soil, page 24. In the alkaline lakes the carbonates, especially lime carbonate, are deposited as calcareous tufa (see page 157) in many striking

and curious forms encrusting the enclosing rocks of the basin, in some places in huge masses. See Fig. 65.

Detached Salt Lakes. — In some cases salt lakes are known to have been formed by arms of the sea having been detached from the main ocean by the raising of some intervening barrier, such as sand ridges thrown up by the waves and winds producing them on a small scale, or an upraise of the earth's crust on a large one. Or they may have been made by dams formed by rivers, glaciers or other agencies. In a humid climate these would become rinsed out and fresh and thus turned into relic lakes, page 73, but in an arid region they may either dry up and disappear, or become the final evaporating terminus of an inland drainage and thus persist.

Fig. 66. — Map of the former Lake Bonneville; lined areas show present water-bodies.

The Caspian Sea is one of the best known examples of this. It receives the waters of the Volga and other rivers which are building deltas and slowly filling it. Its water has a composition similar to that of the sea, but is somewhat fresher, because a large gulf on its eastern side with narrow inlet is acting as the final evaporating pan and in it the salts are being concentrated and deposited. It is therefore being slowly freshened and is turning into a relic lake. Its former connection with the sea is shown by the chemical similarity of the salts in its waters and by the nature of the animal life it contains, seals, for example, being found in it. It is believed to be the remnant of a great arm of the ocean which once stretched northward, over what are now the steppes of Russia, to the Arctic Ocean.

History of Salt Lakes. — The study of salt lakes and their surroundings reveals the fact that in many cases they are merely the

shrunken remnants of much greater bodies of water that once occupied their basins. Thus Great Salt Lake is the remnant of an inland sea as large as Lake Michigan (about 20,000 square miles) and nearly twice as deep, to which the name of *Lake Bonneville* has been given, see Fig. 66, while Pyramid Lake and its neighbors in Nevada are the pools remaining from a great lake nearly as large as Lake Erie, which has been called *Lake Lahontan*. The evidence for this is found high up on the slopes of the basins where the edge of the old water surface is shown by the line of wave-cut terraces, bars, and beaches, see Fig. 67, such as described later under the

Fig. 67. — Former shore lines and wave-cut terraces of the ancient Lake Bonneville.

work of the sea, and in the deltas and bars made by the incoming rivers and now seen lying on the desert floors surrounding the present water bodies, which were the former lake bottoms. The evidence further shows that these lakes were once filled up and then entirely dried away; were filled a second time and then dried down to their present condition, these variations having been dependent on great climatic changes in these regions. This is also shown by the deposits on their floors; first salt when the lake dried up; then clays washed in when they refilled, and which protected the salt from dissolving, and then another layer of salt when they again dried up. This drying up of lakes and deposit of salts is of great interest for it enables us to understand the presence of salt beds in the rocks and connect them with dry climates and desert conditions in the past in regions which now have humid climates and a very different character.

In this connection the history of the Salton Sea is instructive. The Gulf of California once extended far beyond its present limits into California. The Colorado river discharging into this, built its delta as a great dam across the gulf, shutting off its upper portion from the sea and converting it into a salt lake, a relic sea. The river flowed down the south slope of its delta into the sea; and the lake, thus left without inflow in an arid climate, gradually dried away, leaving a vast desolate salt-encrusted basin, known as Death Valley. Recently, in the attempt to divert a portion of the Colorado out on the northward slope of the delta for purposes of irrigation, the river in a period of flood got beyond control and flowed again into the basin, partly filling it up and forming a lake 450 square miles in area and 80 feet deep, known as the Salton Sea, see Fig. 68. After great expense and labor the river has again been forced back into its seaward channel and the lake, thus accidentally rejuvenated, will again in time dry up and disappear.

Fig. 68. — Delta of the Colorado river, showing distributary channels, canals and Salton Sea.

CHAPTER IV

THE OCEAN AND ITS WORK

General Characters. — The ocean covers nearly three quarters of the globe. We are apt to consider its surface as that of a true sphere, everywhere the same distance from the center, and to use this as a datum plane "sea-level," but this is far from being correct. Aside from the fact that the earth is not a true sphere, but a spheroid so flattened at the poles that the polar diameter, on which the earth revolves, is 27 miles less than one in the plane of the equator, the surface is also distorted by the waters being drawn against the continental masses by their gravitational attraction. Thus the sea-level is higher on the coasts than far out at sea, and higher on some coasts than on others where high land-masses, like the Andes, are close to the shore. The vertical differences of level are so small compared with the vast horizontal scale that we cannot detect them by ordinary observation.

The average depth of the sea is about $2\frac{1}{2}$ miles (13,000 feet), varying somewhat in the different oceans. The relief features of

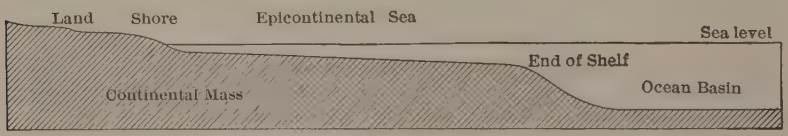


Fig. 69. — Section through edge of continent into ocean basin.

the globe naturally divide into two great classes, continental areas and ocean basins; the amount of ocean water is so great, that not only are the deep basins filled, but also somewhat overflowed, so that a border zone, around most of the coasts of the land areas, is covered to a depth of about 600 feet. These slightly submerged portions of the continents are known as the *continental shelves* or platforms, and it has been estimated that over 10,000,000 square miles, or 7 per cent of the ocean's bottom, forms their total area. Those parts of the ocean which lie upon them are called *epicontinental seas.* (*epi*, upon, or above). See Fig. 69. These relations are of great importance, for, as will appear later, the continental shelves and epicontinental seas have been in the past, as they are at present,

places where processes and results of profound geologic significance occur.

Off the Atlantic coast of North America the continental shelf is broad, about 100 miles, or so, while on the Pacific side it is narrow, about 10 miles wide, from Mexico northward to British Columbia where it begins to broaden. California and Oregon therefore slope quite sharply down into the Pacific basin.

The ocean bottom, in general, is monotonously level and without the smaller relief features, the hills and valleys, of the land. Nevertheless, on a large scale there are swells and depressions rising above and sinking below the general floors of the oceans. The greatest depth in the Pacific, not far from the Ladrone Islands, is the Challenger or Nero deep, sounded to 5269 fathoms, 31,614 feet; near the coast of Japan is another deep of 28,000 feet. In the Atlantic the greatest deep, of 27,000 feet, is off Porto Rico. These *deeps* correspond in character with the highest elevations of the land, up to nearly 30,000 feet in the Himalaya Mountains. The earth and the ocean are on such a vast scale, as compared with man, that it is difficult to realize what a mere film, relatively, the sea is upon the surface of the globe. If a ball three feet in diameter were dipped into water and withdrawn the film of wetness adhering to it like a skin of varnish would represent the ocean.

It is quite certain that sea-level has changed very often during past ages, not only locally by the relative rise and fall of land areas, but absolutely by increase in the actual volume of water. This point will be considered further in several places, where it is a matter of importance.

Chemical Composition. — The chemical investigations which have been made of sea water, from various parts of the world and at different depths, show that the composition of the ocean is remarkably uniform. A large part of the known chemical elements have been detected in sea-water, including gold, silver, copper, barium, strontium, rubidium, boron, fluorine, and others, but most of these substances are present in such minute amounts that they have no practical interest or geologic importance. The percentage of salts in sea-water is about $3\frac{1}{2}$, distributed as follows:

100 lbs. of sea-water contain 3.5 lbs. of salts and 100 lbs. of these salts contain approximately,

	Lbs.
Sodium chloride, $NaCl$	77.8
Magnesium chloride, $MgCl_2$	10.9
Magnesium sulphate, $MgSO_4$	4.7
Calcium sulphate, $CaSO_4$	3.6
Potassium sulphate, K_2SO_4	2.5
Calcium carbonate, $CaCO_3$	0.3
Minor constituents	0.2
Total	100.0

From this it is seen that the chlorides and sulphates of sodium, potassium, calcium, and magnesium are the main substances, with common salt, NaCl, greatly predominating. In addition to these

salts sea-water contains dissolved gases, chiefly air and carbonic acid gas, CO_2, whose amounts vary according to temperature and depth, and accordingly in the past as the ocean has been under glacial or warm climates. Roughly, as an average, we may say that each liter of sea-water contains about 20 cubic centimeters of air, which is much richer in oxygen than the atmosphere, and about $4\frac{1}{2}$ hundredths of a gram of CO_2. The importance of these gases is very great, for upon the supply of oxygen depends the life of the organisms in the sea, while the carbon dioxide, CO_2, whose total quantity is at present about 20 times that in the atmosphere, acts as a regulator of the amount in the air and, since the average temperature over the world depends in part on the carbon dioxide contained in the atmosphere, variations in the quantity in the sea, and therefore in the air, in past times have been, as we shall see later, one factor, in addition to others, productive of great changes in climate and in geological processes.

Functions of the Ocean. — These are somewhat similar to those which have been mentioned as being performed by lakes, but on a vastly greater scale. The ocean acts as a regulator of climate over the world through the great currents moving in it, and especially aids in equalizing the temperature of adjacent land areas; through its waves and tidal currents it is an energetic agent of erosion which destroys the land; it is the final settling reservoir in which are deposited the sediments brought down by the rivers, as well as those produced by its own erosion of the coasts, and lastly it uses this material in a constructive manner in the production of islands and other features peculiar to coast lines. All of these functions are worthy of attention, but since, as will be noted from what is stated above, they so largely depend on the various movements of the waters of the ocean, it is well to consider these first. For if the ocean were still, inert, it would have little effect as a factor in geological work, compared with what it now performs. Its movements may be divided into three great classes: *ocean currents*, *tides* and *tidal currents*, and *waves*.

Ocean Currents. — Driven by the prevalent trade winds, there is, in either great ocean in equatorial regions, a broad current moving westward, along the surface. When this strikes the continental coasts it divides, one part turning northward, the other southward, and each circling returns to the equatorial belt, thus making in each ocean a vast eddy, one north, the other south, of the equator. In the same manner there is a circling movement in the Indian Ocean. These main currents are shown in Fig. 70. In the center

is a more quiet area, known in the North Atlantic as the Sargasso sea. When these broad slow movements, which are known as *drifts*, approach the coast lines the water, by its accumulation and the configuration of the land, may become confined and hastened in its motion giving rise to *streams*. Thus in the North Atlantic the equatorial current striking the north coast of South America is deflected northward. A part enters the Caribbean Sea and the Gulf of Mexico whence it issues through the greatly confined straits of Florida and passes north east into the Atlantic as the well-known Gulf Stream. Its velocity as it comes from the straits is nearly 100

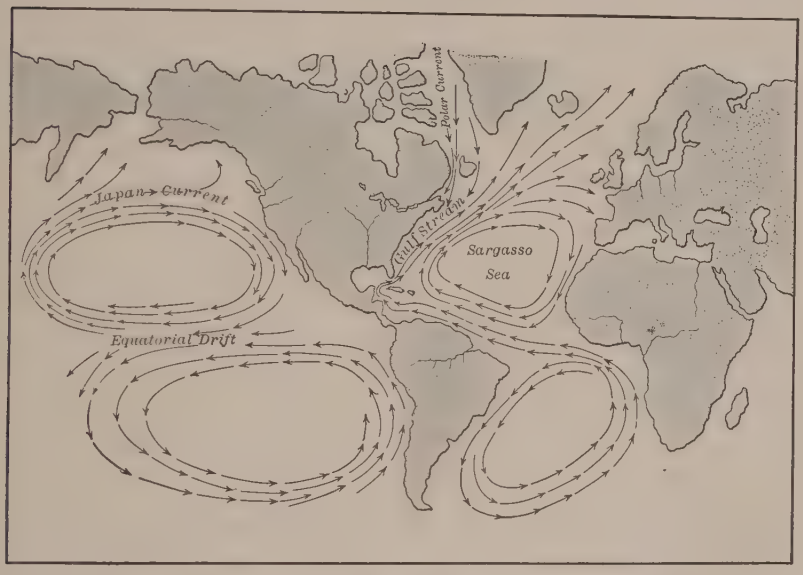


Fig. 70. — Map showing main ocean currents and drifts.

miles a day, but this diminishes as it approaches mid-ocean, and as it grows larger and broader. Finally its motion sinks to 10 miles a day and it becomes a general drift of the ocean waters as it approaches the shores of Europe. Here it divides and one part turns southward to pass along the coast of Africa, and so to join the westward equatorial drift again. Another portion passes northward into the Arctic sea, and to balance this a cold current comes down from the coasts of Greenland around Newfoundland and through the straits of Belle Isle, past Nova Scotia and New England, and gradually passes under the warm surface current of the Gulf Stream.

In a similar way in the North Pacific a current turns northward and eastward and then turns southward along the western coast of North America. It is

known as the Japanese current. These warm currents moving into northern latitudes have a great effect upon climatic conditions in the lands whose shores they strike. The air warmed by the water moves, in its eastward course, inland on the western coasts of Europe and North America and these coastal regions therefore enjoy a mild and equable climate. But in the same latitude, on the other side of the Atlantic, Labrador and Newfoundland, bathed by the cold waters of the returning Polar current, have much colder or even sub-Arctic climates. Thus the ocean currents, like the atmosphere, in taking part in the general circulation on the surface of the globe, are great distributors of heat. They carry warmth into the Arctic seas and, returning as cold currents, they bring with them its ice masses to be melted in warmer regions. Were it not for their agency ice would continually accumulate in the Polar regions and, while in general they perform no direct geological work, indirectly, in what they accomplish, they affect geological processes and are, as we shall see later, of great importance. In some places, as in the straits of Florida, they may scour the bottom, but such action is infrequent and of small account compared with the work of the currents next to be considered.

Tides and Tidal Currents. — Without going into elaborate explanation it may be briefly stated that the tide is an uplift, or huge wave, of the ocean caused by the attraction of the moon and to a lesser degree of the sun. Were there no continents it would pass around the world in nearly 24 hours, and as there are two such upraises, one on the side of the earth next to the moon, the other on the side opposite, there are two such waves, or tides, each day. In the open ocean, its height is so low and its base so vast, that it is not detectible as a wave in passing under a vessel; but on striking the coasts, as it does every 12 hours, it first piles up upon the shore and then recedes, producing the familiar phenomenon known as the tides. The time interval between tides is 12 hours and 26 minutes, and this interval of 26 minutes explains why the time of high and low water progressively changes each day. The effect of the tide on the coast depends greatly on the configuration of the latter, on projecting headlands its height may be only a few feet, while in narrow bays and estuaries it may pile the water up to many times this.

The Bay of Fundy on the Atlantic coast affords one of the best examples known of the cumulative effect of the tide in a funnel-shaped estuary. At its head in the Basin of Minas tides of 30 to 40 feet are common, while heights of 70 feet are sometimes reached. The difference between high and low tide at the same place in this basin is strikingly shown in Figs. 71 and 72.

The immense bodies of water moving in and out of bays and estuaries and along the coast every six hours produce strong tidal currents which, like rivers, have a twofold geologic function in that they both erode and transport. The work done by tides in scour of the bottom and transportation of material along some coasts is very great. Often in entering a long narrow estuary, at the turn from low water, the incoming tide rushes rapidly forward in an immense wave or series of waves 10 to 20 feet in height called a *bore*, or eagre. Examples are

Fig. 71. — Low tide, Port Williams, Nova Scotia, on the Bay of Fundy.

seen in the rivers entering the head of the Bay of Fundy, the estuary of the Severn in England, the Seine in France, the Hoogly in India, and the Tsientang in China. See Fig. 73. The erosive power of such currents is very great, while the heavily turbid condition of the water testifies to the amount of sediment transported. While minute tides may be detected in enclosed seas and large lakes, such as the Black Sea and Lake Michigan, they are too feeble to be of importance or to perform geological work.

Fig. 72. — High tide, Port Williams on the Bay of Fundy. Same as Fig. 71. A variation of 40 feet.

Waves. — These are due to the impulse of the wind. The water particles may be considered as moving in circles which generate the wave form; while the form advances the water does not. When the circle intersects some obstacle, such as the bottom, when the wave form moves into shallow water, the lower part is retarded, the top rushes forward over it, and this water is given a strong forward motion. This produces the *breakers*, or *surf*, so common a feature along seacoasts. The distance from crest to crest is the *length* of

Fig. 73. — Bore of the Seine advancing upstream.

the wave and that vertically from trough to crest is its *height*. The length of average storm waves in the North Atlantic is 400 feet, the height 20 feet, but in times of great storms the length may be increased to 1000 feet, or more, and the height over 40 feet. Storm waves with breaking crests are known as *seas*, but since waves, which may have a velocity of from 20 to 60 miles an hour, may extend far beyond the storm tract which generated them they may lose their crests and in great part their height, and appear as long heavy undulations of the surface known as *ground-swells*. Both ground-swells and seas give rise to breakers or surf on approaching the coast line.

There appears to be some uncertainty as to how deep the influence of waves on material lying at the bottom extends. It depends on the size of the waves and is therefore less in lakes and enclosed seas, like the Mediterranean, than in the open ocean. Probably 600 feet represents the limit at which fine sand is disturbed off the Atlantic coast, but at from 60 to 100 feet sand, gravel and even pebbles are moved, a fact of importance in considering the geological work done by the waves.

The water thrown on the shore by the surf returns seaward in a bottom current called the *undertow*. Where waves strike a shore obliquely the run of the water, due to successive impulses, generates a current along shore. While this may be too feeble in itself to transport material, when the latter stirred up by the waves is held in suspension and carried out by the undertow, the *littoral*, or shore current, may move it along. It is by this combined action of waves and wind currents that material is moved along the shores of lakes which have no definite, or regular, currents. In the North Atlantic the heavy storms are northeasters and waves coming from this direction strike a blow glancing southward along the coast; to this is attributed the presence of rock débris in the beaches far southward from its place of origin.

The force of waves may be very great. According to Stevenson the force with which the average waves of the North Atlantic strike in summer is about 600 pounds per square foot; in winter over 2000 pounds. Blocks of rock 10, 20, and 50 tons or even more in weight have been moved by heavy breakers, while large bowlders are tumbled in the surf like pebbles. In this connection it should be recalled that the transporting power of water varies as the sixth power of the velocity, as demonstrated under rivers, page 41. These facts should be borne in mind when erosion by waves is considered later.

Destructive Work of the Ocean: Erosion

Ever restless is the sea; storms arise upon it and the storm waves strike upon the shore; storms pass and subside but the surging ground-swell continues and steadily breaks in surf, beating on the coast. The surface of the ocean, like an ever-moving horizontal saw, is ceaselessly cutting, gnawing, eroding the land. This it does in several ways, producing, according to circumstances, a variety of features which are worthy of consideration.

Wave Erosion. — Sea-water has more or less solvent action on various kinds of rocks, tending to disintegrate them and thus helping the work of the waves. The work of the latter is, however, chiefly mechanical. Most rock masses have crevices or larger cracks in them and the air or water in these, driven violently in by the impact of the waves, acts as a wedge, disrupting them, and often dislodging large pieces. In this way heavy masonry is often torn asunder. The water rushing into cavities and suddenly retreating leaves a partial vacuum which tends to suck away portions of the roof and sides, and the constant repetition of this gives rise to sea-caves, blowing holes, and spouting rocks, so frequently seen on rocky coasts. But the chief eroding action is accomplished by grinding, and in performing this work the waves use as tools the dislodged material and that which falls from above through atmospheric agencies and which would naturally form a talus at the foot of the sea-cliff. The constant striking and grinding, not only of sand and gravel, but, as mentioned above, of even heavy bowlders render

the waves formidable agents of destruction, through whose work even the hardest rocks are rapidly worn away.

In order to accomplish this waves must have tools to work with, as stated above. Aside from the mechanically disrupting process, waves of pure water have little eroding power. This is strikingly shown in places on the coast of Norway, where through subsidence of the land, headlands are brought into water too deep to be affected by coastal débris. The rock surfaces, smoothed and furrowed by former action of glacial ice, still retain these characteristic features, though subjected to the constant washing of the waves.

In this process the material used by the waves is itself ground up and consumed — reduced to sand and silt. It loses its angular character and becomes *rounded*, the characteristic form of coastal débris submitted to chafing by the waves, and similar to that of pebbles which have suffered long transport in rapid streams.

For the process of wave erosion to continue, the ground-up material must be removed, like sawdust from the track of the saw, in

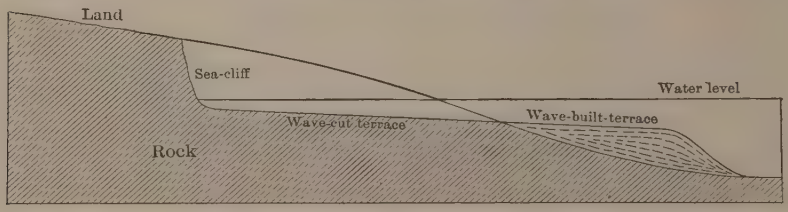


Fig. 74. — Diagram illustrating the production of a sea-cliff, wave-cut terrace and the wave-built terrace.

order that fresh rock-surfaces may be exposed to attack, otherwise the fine material would act as a buffer to receive the blows of the waves and would prevent further erosion. This removal is done by the undertow, which takes the débris back into the sea, and also by tidal and littoral currents, which carry it away. What they do with it we shall presently see. Were it not for the aid of these agencies wave erosion would cease, except where the sea might be invading a continually sinking land surface.

Sea-cliff and Terrace. — The effective erosion of waves is confined to the narrow zone within which they work. The vertical height is of course increased by the lift given to the surface by the tide. This perpendicular distance may be considered the width of the cut, made by the horizontal saw, which the surface of the sea forms. Fig. 74 shows this cut made by the waves into the land. As this process goes on, by undermining, and aided by the action of weathering, material is dislodged from above, falls, and is ground up,

and thus the sea-edge is terminated by a *cliff*, where it is advancing inland on higher country. Beneath the surface of the sea at the foot of the cliff lies an area covered with shallow water, or even partly exposed at low tide, which marks the lower limit of wave action. This is called the shore platform, or *wave-cut terrace*. By the action of sand and shingle, swept about by the washing of the waves and the undertow, the terrace is ground away downward and slowly deepens

Fig. 75. — Wave-cut cliff and terrace. Cape Blomidon, Bay of Fundy.

seaward to the place where the depth prevents such work and material lies at rest. Here the ground-up material accumulates and this deposit is known as the *wave-built terrace*. These relations are shown in the diagram Fig. 74 and the view in Fig. 75 is of a sea-cliff and wave-cut terrace in rock at its foot.

The nature of the sea-cliff depends very much on the character of the material attacked by the waves; thus in hard rocks it may be very steep, perpendicular, or even overhanging; in sand, since the latter would be undergoing constant undermining and sliding down, no steeper angle than that of sand at rest. It also depends on the relative rate of weathering as compared with that of wave cutting; thus clay, which is very tenacious, but easily cut by the waves, may present bold bluffs though of soft material, while granite which is very hard, and attacked and worn with difficulty, may, through its cracks and joints, be subject to more rapid disintegration by the action of frost (see page 20) and the chemical effect of salt water and thus present a sea-front of low slope. It is thus, not so much the actual hardness of the material, as its relative resistance to the two kinds of wear, wave erosion compared to weathering, which determines the nature of the front which the coast presents to the sea. What

was said, page 46, regarding the form of river valleys may be considered in this connection.

Such a bench, or terrace, cut in rock and terminated inland by a cliff, and often with characteristically rounded pebbles and shingle lying upon it or heaped at the foot of the steep, is a decisive sign of surface water-work, either of the sea, or of a lake. And by finding these inland, removed from the present water edge and higher than its level, we are able to recognize that a change of the water-level has taken place; either that the land has been raised, if bordering the sea-shore, or that the water-surface has sunk, if about lakes and inland seas. Thus the terraces about Great Salt Lake, far up on the slopes of the basin and above the present lake, which are shown in Fig. 67, prove to us that the basin was

Fig. 76. — Irregular coast-line produced by erosion in nearly vertical rock strata. Pembroke, Wales. Geol. Surv. of England and Wales.

once filled to this height. The series of benches show the successive levels of the lake formed in the process of its drying up. Many other similar instances of wave-cut terraces, or shore-lines, elevated above present water levels could be mentioned, such as those about the Baltic Sea, which prove elevation of the land. See Fig. 182.

Some geologists, more especially in the past, have believed in the wide extension of shore platforms and have ascribed large areas of level land, composed of worn down rocks, to long and vast inroads of the sea and to subsequent uplift; they have been called plains of marine denudation. But without denying the possibility of such planing off of the land by the ocean it is more probable that where level, or nearly level, regions have been made by the obvious wearing down of former uneven rock surfaces this has been accomplished by atmospheric erosion, by base-levelling and peneplanation, as described on page 65.

Irregularities of Coast-line. — The sea, advancing upon the land, finds materials of very different kinds in different places to oppose its progress, and thus upon the nature of the rocks and their disposition the characters of the coast-line, especially with respect to its minor features, very largely depend, see Fig. 76.

Thus if the rocks are composed, as is frequently the case, of parallel concordant layers or beds, called strata, and their edges are exposed to the waves, the weaker, softer layers are rapidly worn away and the harder beds, left unsupported, break away in blocks. If the beds are horizontal, the harder layers may project for a time as table rocks with cavities under them, as on the coast of Lake Superior. If the beds are vertical, or inclined, but with edges exposed, the hard layers stand out like columns or ribs. If the face of the beds is towards the sea, erosion is slower because the hard layers form an apron, or wall, to

Fig. 77. — Sea-cliff and stack, the latter a remnant of the former land now eroded away. Coast of Wales. Geol. Surv. of England and Wales.

protect the soft layers behind them. If the rock masses are homogeneous and hard, like trap or granite, the irregularities are largely determined by the joints, or regular system of cracks in them, and how these are disposed toward the sea front. Finally, if along the coast there are here and there hard masses with softer ones intervening, the latter are worn away and make coves, while the more resistant masses project as headlands. Thus a bold coast facing the sea is liable to show many minor irregularities of topography.

The sea in its production of an irregular shore-line by dissection of the coast, may cut off portions of land and turn them into islands.

Or the portions thus isolated may be bold masses of rock of varied form and appearance, scarcely large enough or far enough from the sea-cliffs to be dignified as islands, which are known as *stacks* or chimney rocks. They are illustrated in Fig. 77 and are common features in various places, as on the coasts of Great Britain.

Submerged Coast-lines; Estuaries. — The shores of many countries, of which the coasts of eastern North America, of Norway, of Alaska, and of southern Chile may be cited as examples, present

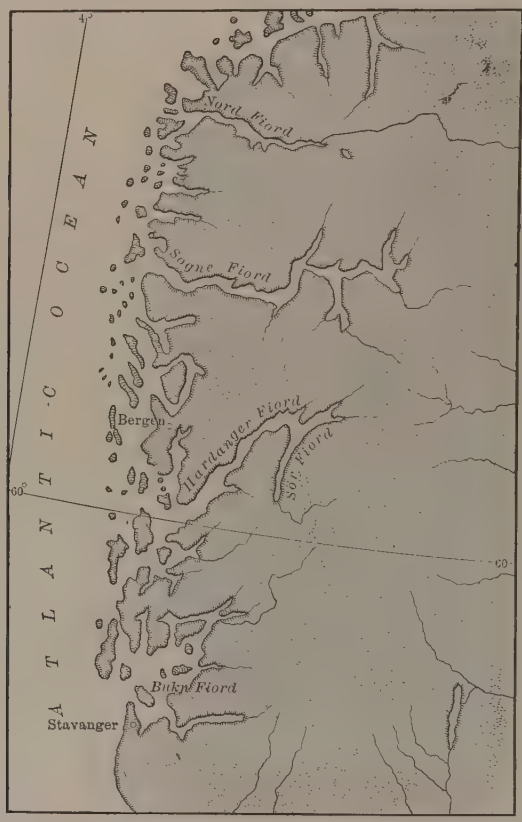


Fig. 78. — Map of a part of the west of Norway, showing the fiords and outer islands of a submerged coast-line.

deeply indented outlines; usually there is an outer fringe of islands and behind this are many long bays retreating inland and forming *estuaries* into whose heads the rivers empty. This is illustrated in the map of a portion of the coast of Norway, Fig. 78, where these estuaries wind back into the country for great distances, 100 miles

or even more in some cases, are very narrow and deep, and often bordered by precipitous walls from 1000 to 3000 feet high, and are known as *fiords*. A view of one is seen in Fig. 79. Somewhat similar fiords are found in Alaska and Chile.

It is impossible to believe that coasts with outlines indented deeply on such a scale could have been made solely by the action of

Fig. 79. — The Sogne fiord, from Gudvangen, Norway.

the waves, and the only satisfactory explanation for them is that they represent tracts of country with very irregular topography, which by gradual sinking have in part become lower than sea-level, and whose valleys have therefore been submerged, or drowned, and turned into estuaries. The fiords consequently are great canyons whose lower ends by sinking have been flooded and turned into arms of the sea, while Delaware and Chesapeake Bays and Long Island Sound are wide and open valleys which have been submerged. That the estuaries along the Atlantic coast have been made in this way is further proved by the fact that the extensions of the present river channels, or valleys made when the land stood emerged, have been traced by soundings as deep furrows across the continental shelf. The drowning of river valleys by submergence has been previously mentioned on page 66.

The outer fringe of islands are the tops of hills and more elevated tracts, nearer the former shore, which by advance of the sea have been cut off from the

mainland. It should also be remembered that, while the larger features of these shore-lines are due to submergence, subsequent wave work and erosion has done much to modify them and to give them their present aspect.

Such estuaries are gradually being filled by the streams which empty into them. Their deposits, which may be considered as the equivalents of their

Fig. 80. — Former drowned valley forming an estuary, now filled by deposits and changed to a tidal marsh. Cohasset, Mass.

deltas, are found at the heads of the estuaries forming level stretches of salt-water marshes, or tidal flats, as illustrated in Fig. 80, now flooded by fresh water from the river, now covered by salt water from high tide. The extent to which these tidal marshes have advanced and filled an estuary depends on its size and depth, and on the volume of material furnished by the inflowing streams. See also drowned rivers, page 66. Such estuaries from the in- and outflow of the tide are subject to strong tidal currents, which carry away in part the sediment brought in by the rivers and thus make less rapid the progress of marsh extension at its head. The material thus swept up and down the estuary is often partly deposited in quiet nooks and corners to form tidal flats and marshes and thus helps in such places in estuary filling. It may be added to by that resulting from wave erosion. Another portion is, however, swept out to sea by the out-going tide and aids in the general constructive work of the waves and currents along the shore.

Constructive Work of the Ocean; Deposition

We have already seen that from a geological point of view a lake must be regarded as a temporary affair; however large it may be, in the vast lapses of geologic time, it would become filled up with sediment and obliterated, if its life is not previously cut short by draining. Although, as previously described, an enormous quantity of material is poured into the sea by the rivers from the erosion and waste of the land, and this is aided by the attack of the waves on the coast, the ocean basins are too enormous to be filled by such

means, for if all of the land were reduced to sea-level and the material spread over the ocean floor the average depth would only be reduced about 700 feet. In other words the oceanic level would everywhere be raised less than 700 feet.

But as the material resulting from the wear of the land is mostly deposited in shallow water, in a relatively narrow zone on the continental shelves, by its concentration it becomes a matter of geological importance and, since much of it lies within reach of the action of waves and currents, it is used by them in the construction of new shore features which are of interest to consider. But sediments of this nature, along the shores on the continental shelves, are by no means the only ones occurring on the ocean floor, for even over the bottom of its deep basins and produced by several agencies deposits are taking place. We may thus classify under two heads the oceanic sediments, *shallow-water deposits* and *deep-sea deposits*. We will first consider the former.

Beach. — This is the familiar feature which distinguishes the edge of the sea, or lakes. It consists of the material which is being worked over and ground-up by the waves. Its upper edge is often marked by a belt of coarser material thrown up and left by the heaviest waves. Lower down it consists of the finer sand and shingle swept in and out and spread by the waves, undertow, and littoral currents. See Fig. 81. Often beaches are inconspicuous or wanting at the foot of steep sea-cliffs and on the contrary are finely displayed at the end of coves and bays, often in curving outline, the reason being that the constant agitation of the waves at the exposed headlands keeps the ground-up material in suspension, and the tidal and littoral currents carry it away along shore until it is deposited in these quieter and more sheltered places. This is especially true in lakes. See page 89. A view of a beach thus formed is shown in Fig. 82.

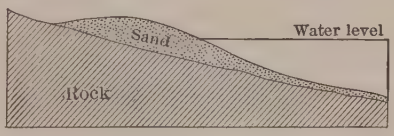


Fig. 81. — Section of a beach, after Gilbert.

It is evident that as the ocean advances on the land by its erosive work its edge is marked by the constantly progressing beach. If this should take place on the side of a continental mass which is sinking the advance of the beach inland becomes more rapid. In a subsiding land area, then, every part is first swept over by a beach line before it becomes the ocean bottom. The consequences of this are marked and of great interest as will be developed later. Beaches have certain marked characters which are described under stratification

and by means of them we are able to recognize the fact that what are now land surfaces have been many times lowered beneath the sea and again raised.

The sands spread out on the beach become dry on the retreat of the tide and waves. They are then subject to the action of the atmosphere. Since along

Fig. 82. — A curving beach. Conception Bay, Newfoundland. C. D. Walcott, U. S. Geol. Surv.

coasts the strongest winds are apt to come from the sea the sand is lifted and dropped inland forming sand-dunes, as described on page 14. Hence, on low coasts, lines of sand-dunes back of the beach are a very common feature.

Barriers. — If the part of the ocean bottom forming the continental shelf slopes out, seaward, very gradually, then the deposits brought down by the rivers and the products of wave erosion, which

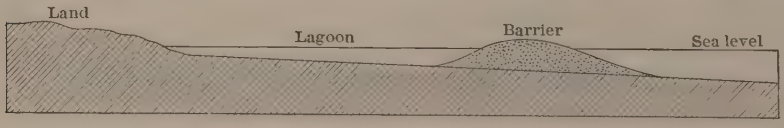


Fig. 83. — Formation of a barrier sand reef.

are spread about on it by the tidal and littoral currents, may be exposed to the action of waves in shallow water at a considerable distance from the edge of the land. When the waves moving landward begin to drag on the bottom the tops moving faster curl over and breakers are formed; the mere wave form here changes to one of actual onward movement of the water, which rushes forward, tearing up the sand and dragging it along. The undertow sweeps the sand and shingle back and the material thus put in motion is heaped up at the point off shore where the struggle between the land and sea

begins, forming a long narrow bar, or barrier, parallel to the general trend of the coast, as illustrated in Fig. 83. The waves beating on this may throw up the sand until it rises to the surface; if broad enough the winds may continue the work, lifting the sand into dunes, and thus a long, low, and narrow island fronting the mainland may be developed. Between it and the mainland lies a stretch of shallow water, rarely more than 20 feet deep, called a *lagoon* if small, or a *sound* if large. They are illustrated in Fig. 84.

It is evident that the distance of such a barrier from the mainland will depend on the seaward slope of the bottom. Off the coast of North Carolina, where the bottom shelves out very gradually, they are far out with wide sounds behind them, as seen in Fig. 84; where the shore slopes sharply off into deep water the barrier may be moved toward the land until it coincides with the mainland beach, or in other words is wanting, as along the coast of California. In Florida it is close in, forming a long, narrow sound known as Indian River.

Such a barrier may be built across the mouth of a river forcing it to flow parallel to the coast for a long distance, or, if the steam is feeble, completely closing the estuary and converting it into a fresh-water lake, Fig. 87, though this is more commonly done by bars, as described in the following section. Ordinarily the sweep of the tide, in and out of such sounds, keeps by its scour channelways, called *inlets*, open to the ocean.

These bodies of water being shallow soon become filled up by the sediments brought into them by the streams and spread by the tide, and by accumulations of animal life, such as shells, etc., and of vegetable matter, such as peat. Thus they become converted into tidal flats and brackish or salt-water marshes and these by further growth of vegetation and upbuilding, or by draining through the agency of man, into, eventually, tillable lands. Thus through erosional wear and transfer of material the coast-line is transferred seaward and the continent lowered and broadened out. By this means the Atlantic coastal plain of the Southern States is being widened, and the maze of sea-islands, with shallow sounds and tidal inlets, along their coasts has been formed.

Fig. 84. — Map of North Carolina coast, illustrating the barrier beach and enclosed sounds.

The student will notice that through the formation of barrier islands a much indented coast-line may be simplified. Thus an inspection of Fig. 84 shows the skeleton framework of the future coast of North Carolina; when the sounds

are filled its coast will be much shorter and have a very different outline from its present one.

Bars and Spits. — We have already seen, page 57, that when a river enters the sea, or a lake, that the sediments it deposits form bars at its mouth. This is, however, not the only way in which bars are made, for they are formed by littoral and tidal currents as well, and those at the mouths of rivers may be much modified as to their disposition by such currents. The essential difference between bars and the barriers which have just been described in the previous section is that the latter are due to waves while the former are made

Fig. 85. — View of a spit. Duck Point, Grand Traverse Bay, Lake Michigan. I. C. Russell, U. S. Geol. Surv.

by currents, though eventually they may become modified by waves. A current moving along shore may carry sediment in suspension, especially if the water is agitated by storm winds (and this applies particularly to lakes where shore currents are feeble); if it now comes to a narrow indentation of the coast it tends to move across its mouth, rather than to follow its shore, and coming into deeper water it is slowed and the sediment deposited. Thus the current tends to build up an embankment across the indentation and to form a bar. The necessary conditions are that the current should be fed with sediment from the beach along which it moves and that it should proceed into deeper water where it slows up and deposits its load. When the current has built the deposit up to the point that the waves may begin work upon it these may still further heap up the material until it becomes land, and the winds, by raising dunes

upon it, may increase its height still more. If the embankment projects out with a free end it is called a *spit*, but if it closes, or nearly closes, the indentation of the coast it is a *bar*. See Figs. 85 and 86. Commonly the scour of tidal currents, rushing in and out of the bay, prevents complete closure and leaves an *inlet;* but it sometimes happens, and the enclosed water-body, after it has been rinsed out by

Fig. 86. — Island tied to mainland by bar. Bay of Fundy, Nova Scotia.

the drainage passing into it, becomes a fresh-water lake. Thus by the formation of bars and barriers, or combinations of them, numerous small lakes and ponds along the coasts have been made. Many excellent examples are found in New England, as illustrated in Fig. 87. Spaces between islands or between an island and the mainland are often favorable places for the formation of a bar and it is common to find islands tied together or to the mainland by them, as illustrated in Fig. 86. These occur also in lakes.

In an estuary affected by the tide, there is a body of water, which, somewhat like a pendulum, oscillates back and forth every six hours carrying sediment in its rush. At high tide it is at the end of its swing upstream and has checked the down coming water of the river; here where quiet water for a time ensues, sediment will be deposited and a bar formed at the head of the estuary. In its downward swing the water rushes out to sea and at the mouth of the estuary at low tide quiet water ensues, sediment is dropped and bars formed, in this case modified by littoral currents as to their shape and disposition. Thus in the Hudson, which is really an estuary for more than 100 miles above its mouth, the upper bar is not far below Albany while the lower bars obstruct the entrance to New York Harbor.

Bars at the mouths of harbors and of great rivers, such as the Columbia below

Portland, Oregon, are a great obstacle and menace to navigation. Although often partly removed by dredging to permit the entrance of vessels, in the nature of things, as will be seen from what has been stated, they cannot be permanently removed, because they renew themselves, and thus they remain a constant problem in engineering work.

Bars may also be found in shallow seas or on the continental platforms at considerable distances from land by the action of tidal currents. Thus the material brought down by the rivers of southern England and northern France into the British Channel, and that worn from their coasts by wave erosion, is in large part swept by the tidal currents into the North Sea, where the currents

Fig. 87. — Map of coastal fresh-water ponds. Rhode Island.

meeting the advance of the tide coming into this sea from its northern opening come to rest at high tide, and deposit their load of sediments, forming the numerous shoals and bars which characterize the bottom of this sea.

Deep-water Deposits. — The deposits which have been described in the foregoing sections, and which are used by the ocean in its constructive work of making beaches, barriers, bars, and islands, are very largely those occurring in very shallow water close to the land, where the greater part of the land waste is laid down. But in addition to these, as was intimated in a previous section, deposits are laid down in *deep* as well as in shallow water, and indeed one may say that, of one kind or another, they are formed everywhere on the floor of the sea. Since in several ways they are both important and of interest, they deserve consideration.

Going seaward from the land we may, for practical purposes, divide the ocean bottom into three zones or regions, the continental shelves, the intermediate slopes, and the profound abyss, as illustrated in the diagram, Fig. 88, each distinguished by certain characters as well as, in a general way, the deposits occurring on them, as follows:

The Continental Shelf. — This has been already described. In general it is limited seaward by the depth of 100 fathoms (600 feet). Taking the whole world into account the area of sea-bottom belonging in this zone is about 10,000,000 square miles. It can be subdivided into the *littoral* or beach region, between high- and low-water marks, and the *shallow water* area, beyond low-water mark and therefore never exposed to the air. The littoral zone covers a relatively small space, estimated at about 62,500 square miles for the world.

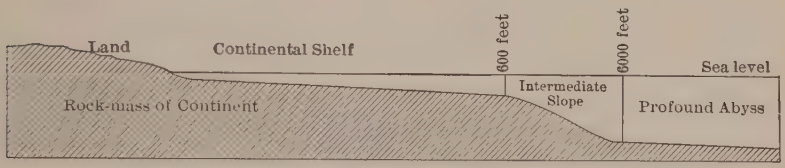


Fig. 88. — Diagram showing different ocean zones.

Epeiric Seas. — The shallow water area, in addition to the epicontinental seas covering the continental shelves, as previously described, includes basins more or less enclosed by land which the overflooding of the ocean has filled with salt water. Seas enclosed by land may be divided into two classes, as follows: first those which are very deep, and through geologic periods, without regard to relative changes of level in land and sea, have maintained themselves as water-bodies; and second, those formed in depressed tracts or downwarps of the continental masses which have in times past experienced great changes through variations of sea-level, sometimes being more or less completely emptied of their water, or filled with sediments and turned into land. Examples of the former class are to be seen in the Mediterranean and Carribean Seas, which are very deep, while Hudson Bay, the Gulf of St. Lawrence, and the Baltic Sea are existing examples of the second class. Such shallow seas as these latter, from their relations to the continents, may be termed *epeiric seas* (Greek, ἤπειρος, a continent), and those of North America, as we shall see in the second part of this work, have been in the past the theater of important events.

Characters of Shallow Waters. — In the areas of shallow water described, upon the continental shelves and in the epeiric seas, the following characters obtain. The waters are more or less agitated to the bottom by wave movements and are kept in motion by tidal and ocean currents. They are influenced by external temperatures, and thus experience seasonal changes from warmer to colder and

the reverse. Over the floor of these continental shelves and basins the deposits are chiefly those sediments coming from the land, *terrigenous* (born of the land) as they are called, mainly sands with occasional areas of muds. In some places, where land sediments are scanty, or wanting, as in shallow water districts about the south coast of Florida, or in the open ocean, the sediments may be those produced by organic life, as described later under that agency, and are then mainly composed of carbonate of lime, such as shells of various kinds, corals, etc.

In this zone, owing to the conditions described and to the fact that light penetrates freely, various forms of life are abundant on the bottom. Vegetation, such as seaweeds (*Algæ*), flourishes and upon it are nourished different kinds of vegetable-eating animal organisms such as certain snail-like shell-fish, herbivorous Gastropods, and worms for example, and upon these live carnivorous, or flesh-eating, animals such as certain kinds of fish. A large part of the commercial food-fishes live in this region. The plants and animals of the shelves, owing to the presence of light, exhibit colors, of different tints, which are often remarkably brilliant and varied. There is also in the sea an immense quantity of minute floating forms of vegetation (*Algæ*) and upon these microscopic plants various animal organisms subsist, to be themselves devoured in turn. This floating life is the great magazine of food.

The abundance of life in the sea varies much between cold and warm waters, and this in turn depends on food supply and oxygen. Of the chief foodstuffs there is usually an ample quantity; the determining factor appears to be the amount of certain substances needed by life in small quantities which are brought from the land into the sea by rivers. Nitrogen in some form of combination, phosphorous, and silica, are examples of this. It is thus easy to see why life is more abundant around sea-coasts than out in the open ocean. Furthermore, in the shallow coastal and epeiric seas of tropical regions it has been found that certain bacteria swarm, which have the property of secreting and precipitating lime from sea-water and at the same time of converting the combined nitrogen into nitrogen gas. But, as is well known, warm waters can contain less gas in solution than cold ones; hence the nitrogen tends to escape and the water to absorb a relatively lesser amount of oxygen from the air. Thus in great measure such seas, deprived in considerable part of the necessary staple of life, combined nitrogen, and with lower content of oxygen, are not favorable for the production of life, first, vegetable and second, animal, which subsists upon vegetable life, in great quantities.

In such seas in temperate or arctic climates, on the other hand, the waters are colder, the denitrifying bacteria do not exist, or are present in small numbers, there is more oxygen in solution, the conditions for life are better, and hence we find their shores and bottoms thickly populated with an abundance of organisms, both animal and vegetable. It is in such waters that the great fisheries of the world are situated. The popular notion that tropical waters must swarm with life because they are warm is quite incorrect, but on the other hand, it is true that the variety of living forms is greater in warm waters than in cold ones, and the amount of carbonate of lime deposited by them is much larger.

The deposits as laid down are in concordant layers, or *stratified*, and exhibit

certain characters described later in detail under stratification; they may contain in great abundance remains of animals, such as shells, etc., and even of plants, drifted into them from the land. Thus this region and its deposits are of great interest, not only to the zoologist and botanist on account of its forms of life, but to the geologist as well, since by study of them he is able to perceive that wide stretches of land, now covered with stratified beds of rock and full of organic remains (fossils), were once areas of shallow sea-bottom which have become dry land, and thus exposed, and to understand the conditions under which the bedded rocks were laid down and the animal life flourished, as explained later in this volume.

The Intermediate Slope. — This constitutes that portion of the ocean bottom out beyond the 100 fathom (600 feet) line to a depth of 1000 fathoms (6000 feet). While the upper border, which is the edge of the continental shelf, is quite well defined, the lower limit is largely one of convenience. It may be considered the wall or side of the true ocean basins, as illustrated in Fig. 88, but it must not be understood that there is always and everywhere a marked change of slope and very sharp descent from the edge of the continental shelf to the profound abyss, for, while this is relatively true in a general way, the slope outward is often a gradual one prolonged for great distances.

In this region, which covers about 18,000,000 square miles of the ocean bottom, the lowest layers of water are not agitated by waves but only by ocean currents of slow movement. The temperature is, in general, fairly constant and not influenced by seasonal changes of heat and cold. However, when warm and cold currents pass near one another there are at times sudden changes and destruction of life. Light is absent, or only very feeble near the edges of the continental shelf, having been absorbed before penetrating such depths. The deposits are only the very finest of the land sediments which have been drifted out. This is especially the situation of the *blue* and *green muds*. The voyage of the Challenger, an exploring vessel sent out by the British Government, showed that even at distances of from 150 to 200 miles the approach to land could be told by these muds.

The lower limit of the muds is indefinite and often extends far out beyond the 6000 feet line. The blue muds have been estimated to cover 14,000,000 square miles of bottom. In places they are replaced by red muds, which should not be confounded with red clays found in the abysses, as on the east coast of South America, and other areas may be in part covered with grey muds composed of volcanic ashes, or by deposits from organic life, as mentioned in the following section.

Owing to the absence of light in this region there is no vegetable life on the bottom, or but a small amount restricted to the zone near the continental shelf. The animal life is mostly confined to certain forms which live upon organic matter in the mud, resulting from decay of the sunken masses of floating microscopic plants and the bodies of free-swimming animals, such as crustaceans, squids, and fishes which inhabit the top layers of water, and of vegetable matter carried out from land by ocean currents. From the small amount of light, or its absence, the living forms are generally of dull colors, yellows and browns predominating. The green color of these muds is given to them by grains of a green substance called *glauconite*, a silicate of alumina, iron, and potash, which forms in the sea. It is also found in some stratified rocks formed in shallow water and thus helps to prove that they were former sea-bottom deposits.

The Profound Abyss. — This comprises the whole area of the ocean bottom below the 1000-fathom (6000 feet) mark. In it are also included the lower parts of the basins of a few interior seas, such as the Black and Mediterranean Seas. The depths attain a maximum of about 30,000 feet. In these profound and monotonous abysses light is absent, there is no movement of the waters except that slow transfer resulting from the unequal heating of the surface of the globe, which carries the cold water of the Polar regions into the depths of equatorial basins. The temperature of the bottom layers of sea-water is that at which it has its maximum density, about 34° or 35° Fahr., or very near freezing.

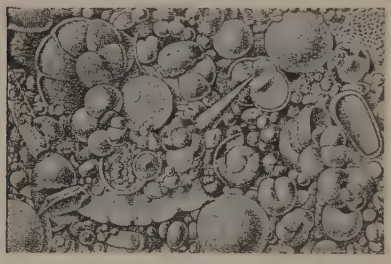


Fig. 89. — Deep sea calcareous ooze, much magnified, containing shells of Foraminifera. (Agassiz and Murray.)

Over by far the greater part of the floor of these abysses land-derived sediments are wanting. Over all of them, however, by sounding, peculiar, fine, soft deposits, called *oozes*, have been found, which in different regions have different characters. These are so soft and fine that water movements of one-half mile per day are stated to shift them on the bottom and it is suggested that the monotonous character of the sea-floor may in part be due to the filling of the smaller depressions by these deposits. There are three ways in which these oozes can originate: *a*, *volcanic*, fine dust from volcanic eruptions carried vast distances by air currents, or volcanic ashes and pumice floating and driven by ocean currents long periods before sinking; *b*, *cosmic*, the particles of interstellar space which the earth gathers in its journey around the sun; and *c*, *organic*, re-

sulting from the shells and framework of organisms living in the surface layers of water. Of these oozes the most abundant are a peculiar *red clay* which covers the floor of the deepest abysses and has been estimated to have an extent of over 50,000,000 square miles, chiefly in the Pacific, and a *calcareous ooze*, resulting from deposition of the shells of minute organisms and estimated to cover nearly as large an area; it is found especially in the Atlantic, Fig. 89.

In the Polar oceans a siliceous ooze occurs, formed from the very ornate shells of diatoms, very minute, simple floating plants whose shell is composed of silica (SiO_2). As the organic oozes do not, in general, occur in the greatest depths, and life is nearly everywhere found in the top layers of the oceans, it is inferred that the calcareous shells are dissolved before reaching bottom and hence are replaced by the red clay which forms as a final residuum, chiefly from the decay of volcanic and cosmic materials. The presence of the latter is shown by the minute balls, obtained in soundings, which contain metallic iron and have various features similar to the meteorites, or "shooting stars," of larger size which fall on the earth's surface.

The dark cold abysses of the deeper ocean are unfavorable to life, yet it is there. There is no ground vegetation and the animals living on the bottom must exist upon the sunken bodies of the plant and animal life living in the upper layer of the ocean waters, to which the collective term of *plankton* has been given. The bottom animals are of rather simple types, such as certain worms and star-fishes, some of which are found at great depths; they exhibit a want of color and are often blind. Some have in themselves the means of generating light by phosphorescence.

No formations have yet been generally found among the stratified beds, which now occupy land surfaces, that are exactly comparable to the deposits now found on the floor of the deep ocean basins, and the conclusion has been drawn from this, that the present continental areas have always existed as such, and have never been sunk far enough to become the bottom of the very deep ocean basins, but only of relatively shallow water areas. Some limited occurrences have been found which are held to be of this nature, and, while continental areas appear to have always remained as such, it is also possible that portions of what was once deep ocean bottom may have been elevated to form lands.

Islands. — These may be divided into two classes, according to the positions which they occupy: *continental* and *oceanic*, the former resting on the continental shelves, the latter rising from the depths of the ocean basins. The oceanic islands, while they may be due to the partial destruction by erosive and other agencies of former continental masses in some cases, like New Zealand for example, are more often caused by accumulations on the ocean floor. Such accumulations are chiefly volcanic in origin, although they may be greatly added to by deposits made by corals, as described under organic agencies. Hawaii is an excellent example of a group of oceanic islands composed of lofty piles of volcanic materials rising about 15,000 feet from the bottom of the deep ocean to a maximum

height of nearly 14,000 feet above its surface. The Pacific is filled with such islands.

Continental islands are to be regarded as unsubmerged portions of the continental shelves, separated from the mainland. Long Island, on the Atlantic coast is an example. As shown in the foregoing sections they may be made in two ways; by the *destructive* action of erosion and by the *constructive* work of waves and currents. The former type is chiefly found along sunken sea-coasts and is due to the submergence of an irregular coastal land surface with subsequent shaping by wave erosion. The islands of the coast of Maine and those about Scotland and Norway are examples. The other, or constructive type, are the low sand islands thrown up as barriers by the waves and illustrated by the sea-islands along the coast of the Southern States. In some cases constructive and destructive work may be nearly balanced and the island represent the result of the two forces; Long Island is an example of this.

Examples of the four classes of islands mentioned are given below:

Type of Island	Made by work which is	
	Destructive	Constructive
Continental.....	Mt Desert Id. Block Island Nantucket Id.	Cape Hatteras Id. Cape Fear Id. Matagorda Id.
Oceanic.....	New Caledonia South Georgia Spitzbergen Fiji	Hawaii Samoa Azores Bermuda

CHAPTER V

ICE AS A GEOLOGICAL AGENT

By far the greater part of the land surface of the globe is covered by snow and ice during a part of each year and over vast tracts of it they exist perpetually. Snow and ice therefore are geological factors of great importance whose work is deserving of careful attention and study. The only difference between snow and ice is that the former consists of loose, freely grown crystals of water, while in the latter the crystals form a compact mass; they are consequently to be considered together, especially as it is the ice that is the agent of importance.

Ice in the Soil. — The work of frost in splitting rocks, and thus helping in the formation of soil, has been already explained on page 20. The expansion of the water in the soil in freezing also causes movement, and a variety of effects. The vertical motion due to this is the reason why posts and other objects buried in the soil are gradually upheaved and overthrown. On slopes it produces a slow downward *creep* of rocks and soils.

The reason for this creep, which may be explained by the aid of Fig. 90, is as follows: When the soil freezes, a bowlder lying on the slope would be lifted by the expansion in the direction *ab*; on thawing taking place it will sink back vertically in the direction *bc*, thus moving down the slope from *a* to *c*. Thus each year it may be considered to take a step down-hill and the sum of these steps produces the creep.

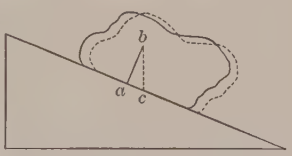


Fig. 90. — Showing downward creep due to frost.

Probably it is due in part to this expansion and movement in ice forming that heavy falls of rock, or slumping and landslides, take place in the springtime in high mountainous regions, especially when aided by the effect of heavy rains. Talus slopes thus tend by creep and sudden sliding to move downward, and where they are extensive may give rise to trains or streams of broken rock material, especially in high mountains, which extend down into valleys. Such rock trains have sometimes been called rock-glaciers, see Fig. 91. What is stated later in regard to landslides on page 159 may be referred to in this connection.

River Ice. — In streams which freeze the ice becomes a considerable factor in transporting material, often of considerable weight and size. Along the shore and at the bottom it becomes cemented into stones and gravel on freezing, and along steep bluffs considerable

Fig. 91. —"Rock Glacier" in Silver Basin, Colo. Whitman Cross, U. S. Geol. Surv.

masses of earth and rocks may fall upon it. When the ice breaks up in the spring more or less of this may be carried down stream attached to the floating ice masses. In narrow places in a river's course the ice cakes may become jammed, forming ice dams, by which the muddy water of the stream is ponded back, overflowing the adjacent lowlands and, as it is thus brought to rest, being made to deposit its load of sediment on the alluvial flats.

Ice in Lakes. — The chief work done by the ice in lakes is accomplished through the thrust which it exerts upon the shore by its expansion. Ice, like other substances, is expanded and contracted by changes of temperature. When a lake freezes the ice cover first formed accurately fits its surface; if the temperature falls the ice contracts and in so doing cracks, water wells upward into these cracks and is frozen, healing the cracks; the cover of ice again fits the surface of the lake at the reduced temperature. If the latter now rises the ice must expand and in doing so exerts an enormous thrust against the shore. By this means loose material is pushed

up into ridges, and bowlders lying in shallow water within reach of the ice are crowded ashore, forming walls of stones, or *ice ramparts*, about the border of the lake, as illustrated in Fig. 92.

Fig. 92. — Ice rampart on Lake Tenaya, Calif. G. K. Gilbert, U. S. Geol. Surv.

The Characters of Glaciers

Perpetual Snow-fields. — On all the continents, except Australia, there are places where the annual fall of snow is not entirely dissipated each year by evaporation and melting. In such places snow lies upon the ground all the year, forming perpetual snowfields. In tropical regions this occurs only on the tops of the loftiest mountains, in temperate regions much lower down, while in polar lands such snow-fields approach sea-level. Thus in passing from the equator to the poles, and depending on average temperature, there is a descending line or surface above which snow lies all the year and which is therefore known as the *snow-line*.

At the equator this line is from 15,000–18,000 feet high, in Mexico 14,000 feet, in Colorado 12,000–13,000, in the Yellowstone Park about 10,000–11,000, in northern Montana about 9000, in southern Alaska about 5000, in southern Greenland about 2000. In the Alps it is about 9000, in Norway about 5000. The snow-line also depends very much upon the annual precipitation; where this is great it may be much lower than in places with a corresponding latitude where the snowfall is light. Thus at the western end of the Caucasus mountains on the Black Sea it is 2000 feet lower than on the eastern end of this range near the Caspian Sea, where the climate is much drier. In Bolivia under the equator it is 18,500 feet on the dry western side of the Andes, 16,000 on the moister east side. It is considerably higher in Montana, with a rather dry climate, than in Switzerland in the same latitude with a moister one. In very dry regions snow may disappear more rapidly by evaporation than by actual melting.

Névé. Change into Ice. — In the high mountain valleys, slopes, and amphitheaters above snow-line, which form the gathering ground, or catchment basins, for the perpetual snow-fields, through the weight of the accumulating annual layers, the snow becomes *compacted* and as it does so it changes in character. From the

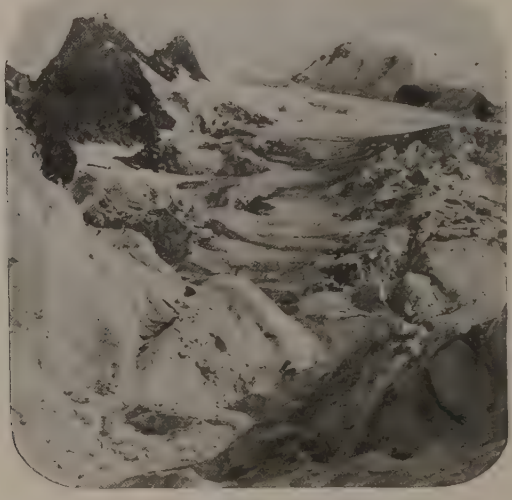


Fig. 93. — The gathering ground of the snows. Névé fields in the Mont Blanc region of the Alps.

loose feathery condition of newly fallen snow it assumes a granular texture like rather coarse sand and resembles the granular snow which we are accustomed to see in the spring as the remains of large drifts from the winter. This is largely the result of alternate thawing and freezing at the surface. The great snow-fields composed of this granular snow are called *névé* slopes, or fields.

Since the study of glaciers, and of the various phenomena associated with them, was first undertaken in the Alps the different names adopted for them are largely the ones used by the French- and German-speaking mountaineers. *Névé* is the French term, *firn* the German one.

Beneath the surface the névé rapidly becomes more compact and passes into porous ice, which in turn becomes denser. This ice is more or less distinctly stratified, or in banded layers, resulting from successive falls or annual deposits having somewhat different consistencies, or being separated, or outlined, by films of wind-blown dust or earth.

Movement; the Glacier Formed. — If we follow the névé down its slope, toward the valley below, there comes a point in the mass of

accumulated ice, which may be 1000 feet, or even much greater in thickness, where *movement* begins and the ice commences to flow slowly down the valley which forms the outlet of the catchment basin above, somewhat after the manner of a river. It flows down the valley to a point where, eventually, it is melted and changed to a river, which carries off the surplus drainage of the basin. The flowing tongue of ice projecting from the upper snow-fields is the glacier proper. Thus in regions above the snow-line, where the annual precipitation is mainly in the form of snow, the drainage, for a certain distance, takes place in part, in the form of ice, giving rise to glaciers.

The point at the surface, where the névé ends and the ice of the glacier is exposed, is at the snow-line of that place. This is usually considered the point where the glacier proper begins, but movement in the ice underlying the névé-fields commences far above this. Very often there is a wide and deep crack, or fissure, or a number of them, between the ice of the snow-field and the adjacent

Fig. 94. — Bergschrund and beginning of the glacier. Mont Blanc region, Switzerland.

rock surfaces of the catchment basin, or from the thinner part of the névé field lying on them, caused by the initial movement of the ice mass away from them, which is known as the *bergschrund*, as illustrated in Fig. 94.

Not every snow-field forms a definite glacier; frequently it is not sufficiently large to produce ice enough to cause movement to be generated by its mass. It is then simply an area of névé, passing into ice below. Such snow patches are common in all high mountains and in some regions, as in Colorado for example, where the combination of mountain heights and amount of precipitation is not

capable of producing snow-fields large enough to form glaciers, they alone are to be found.

Another stage is where the névé fields are sufficiently large to form at their lower ends ice masses which show by various features that movement or flowage takes place, but not on a scale which enables the ice to project any distance below snow-line, or to produce distinct ice tongues flowing down into the drainage valleys. Such masses are variously called *glacierets*, *hanging glaciers*, or sometimes *cliff glaciers*, when nestled in the face of a cliff. Every gradation exists between simple névé patches, glacierets, and glaciers proper. The so-called glaciers found in the Rocky Mountains and in the high Sierras in the United States are nearly all glacierets, although a few are intermediate between these and real glaciers, of what, as we shall see later, are called the valley type. An example is seen in Fig. 95.

Fig. 95. — A glacieret. The Dana glacier in 1883. Mt. Dana, Sierra Nevada, Cal.

A *reconstructed*, or "recemented" glacier is formed where the movement carries a glacier over a cliff, and the mass of fallen fragments below is molded by weight and refreezing into a solid mass, which flows onward as a new glacier.

Lower Limit of Glaciers. — The point to which a glacier may descend below the snow-line before being melted depends on several circumstances. It is obviously a question between the rate of supply and that of melting, and might be likened to the distance a rod of ice could be thrust into a furnace before being melted; this would depend on the size of the rod, the rapidity with which it is

pushed forward and the heat of the furnace. Thus in tropical and warm regions glaciers, in general, project but a short distance below the snow-line; as we go further north, although the snow-line descends, we also find glaciers pushing downward a relatively greater and greater distance from it; and, eventually, as we approach subarctic regions we discover them entering the sea and ending by breaking off in icebergs. The lower limit is also influenced by climatic conditions for, in moist regions, there is a greater precipitation and supply, hence glaciers are larger, more rapid, and descend greater distances below snow-line. Locally, also, in a given region, a large glacier, especially if confined to a narrow channel, descends lower than a small one. As with rivers, so in these streams of ice, if they can go far enough, as in Arctic regions, the ultimate limit is the sea.

In the Alps glaciers project as far as 5000 feet below the snow-line, and in Norway nearly an equal distance. In southern Alaska they come down to sea-level at about 55° N. and also in southern Greenland at about 60°, while in Norway which extends up to 70° N. they fail to enter the sea owing to climatic influences, especially of the Gulf Stream, see page 86. In the southern hemisphere, in New Zealand, which has many fine glaciers in the Southern Alps of the South Island, they descend in latitude 45° S. into sub-tropical forests in which the tree-ferns spread their graceful foliage, and in southern Chile, fed from the Andes, they touch sea-level at about 47° S. latitude.

Classes or Types of Glaciers. — According to the size and features which they possess, the ice-fields of the land surface of the world may be divided into three great classes, or types: *valley*, or Alpine, glaciers; *piedmont* glaciers; and *continental* glaciers, or ice-caps. Each of these may be considered separately with examples, since each is of importance in the character of the geological work which it performs, as will appear presently.

Valley Glaciers. — These are of the class which has already been described in the foregoing, and are essentially the type one commonly has in mind when glaciers are mentioned. They consist essentially of a catchment basin, or area, for the gathering of snow above, Fig. 96, which feeds a stream of ice flowing slowly down a valley and which is the glacier proper, Fig. 97, until through melting it changes to a river. Such glaciers may be compared to rivers, and, as we shall see presently, they have many points in common with them and some marked dissimilarities. Like rivers they may have tributaries, that is, they may be formed of a number of ice streams flowing together and coalescing in a final trunk glacier, as illustrated in Fig. 97. They are the kind of glacier found in the Alps, where glaciers were first studied, and hence are often called Alpine

Fig. 96. — View illustrating the lower limit of glaciers in the Alpine type. Glacier proper begins where snow-line ends. Glacier des Bossons descending from Mont Blanc, Chamounix, Switzerland.

Fig. 97. — Typical valley glacier with branches; lower part of the Mer de Glace in 1875. Moraines of earth are seen on its surface as dark bands. Chamounix, Switzerland.

glaciers; they are the ones characteristic of all high mountain regions, rising above the snow-line.

It has been estimated that there are about 2000 glaciers in the Alps; while most of these are small and of less than a mile in length, a few are from three to five miles, and one is 10 miles long. The average thickness is probably a few hundred feet, the width in the largest a mile. In Norway there are several large plateaus of ice which send down glaciers in several directions into the valleys below. In the United States valley glaciers of some size are found only on the lofty volcanic peaks of the Cascade Range in northern California, Oregon, and Washington, as on Mts. Shasta, Rainier (Tacoma), Hood, Baker, Three Sisters, etc. On Shasta they attain a length of two miles, on Rainier they are larger, up to nearly seven miles. Fine glaciers are found in the mountains of British Columbia, and northward into Alaska, where they are of great size, the Seward glacier being stated as 50 miles long and three wide in its narrowest part.

In addition to the various regions previously mentioned magnificent glaciers, up to 30 miles in length, are found in the Himalayas, while the Caucasus, Nan Shan, and other high ranges of Asia, except the Altai, furnish fine examples. On the high lands and islands of both the Arctic and Antarctic Seas they abound, and even in Africa, under the burning equatorial sun, small ones exist on Kilimandjaro (20,000 feet), and on Kenia (19,500 feet), and in South America on the high Andes of Ecuador.

Piedmont Glaciers. — If valley glaciers, or a number of them, descend far enough out of the mountains into the more level country below, they may give rise to a large area of nearly stagment ice before melting. Such an ice-field is known as a *piedmont* (foot of the mountain) glacier. If we compare valley glaciers to rivers a piedmont glacier might be likened to a lake, a place where the excess of ice through flowage becomes ponded, before melting from its surface and borders. Such glaciers are not common, and are confined to regions of high latitudes, the best known being the Malaspina glacier in Alaska.

The expanded foot of the Rhone glacier shown in Fig. 107 may be considered as the beginning of a piedmont glacier, and illustrates the principle of its formation.

The Malaspina glacier is situated at the foot of Mt. St. Elias (18,000 ft.) and other high mountains which feed it by their ice streams. It covers an area of 1500 square miles and is from 1500 to 1000 feet thick. As may be seen from the map, Fig. 98, it closely borders the sea. It has a nearly level, broadly rolling surface, broken by innumerable fissures. Its borders are covered with earth and stones, like those of other glaciers and described later under moraines (p. 124), and these deposits in places are deep and extensive enough to support areas of dense forest growth, although resting on ice 1000 feet thick. By its melting the glacier gives rise to several rivers, the delta of one of which is seen in Fig. 43.

The Muir glacier in southern Alaska, at the head of the inland passage, may be taken as a type intermediate between the piedmont and valley glaciers. It fills a great basin of about 350 square miles and is fed by ice streams coming from the high mountains which surround it. The lower end of the valley basin touches

the sea and, like a lake with accelerated movement of the water at its outlet, the ice in motion discharges into the head of Glacier Bay between mountain walls, forming an ice-cliff two miles long, from which icebergs are continually breaking off, with an uproar like heavy thunder. At the time of the writer's visit

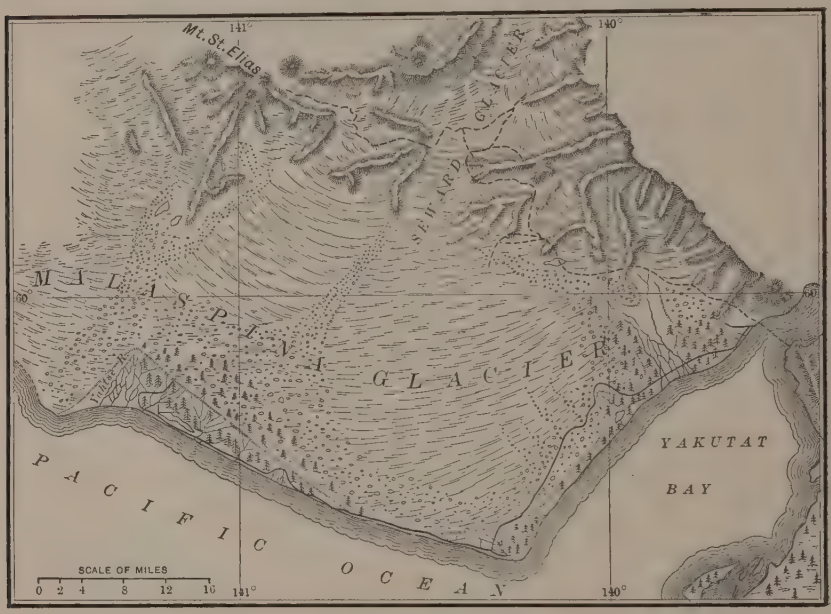


Fig. 98. — Map of the Malaspina glacier, after I. C. Russell.

in 1887 the ice-cliff rose to a height of about 250 feet out of the sea; the depth in front, as ascertained by soundings then made, was over 700 feet, so that the thickness of ice was not less than 1000. A view of this ice front is seen in Fig. 99. The Muir is one of the largest of what have been called "tide-water" glaciers; those which reach the sea.

Continental Glaciers; Ice-Caps. — These, as their name implies, are ice sheets of vast extent. If the two former classes of glaciers may be compared to rivers and lakes these may be termed seas of ice. Their chief feature is the almost endless monotony of broadly rolling, nearly level surfaces of wind-swept ice which they present, a monotony varied only by the continually successive storms of snow which maintain them. Near their borders they are often varied by occasional mountains of rock, rising like islands through the ice and known as *nunataks*. At their borders they thin down into prolonged lobes, or give rise to definite streams of ice which discharge into the ocean, forming icebergs. Only two examples of them exist today, in the ice-caps which cover Greenland and the continent of Antarctica, upon the latter of which the South Pole is situated.

The ice-cap, or inland ice, of Greenland covers an area of probably 500,000 square miles. It has been traversed by Nansen and Peary and, according to these explorers, the great shield of ice rises to a height of 8500 feet. Its thickness is not known but may be several thousand feet. This ice is in motion, as

Fig. 99. — Sea-cliff of the Muir glacier in 1887.

shown at its edges where it becomes more rapid as it descends in valleys to the sea, but the movement in the interior must be almost indefinitely slow.

The size of the Antarctic ice-cap is not known, but may be a million or more square miles in area. It has been partly explored by Scott and Shackleton in their journeys to reach the South Pole. It attains a height of 9000 feet. Like the ice sheet of Greenland it thins towards the sea, and descending through valleys in the mountain rim gives rise to huge moving glaciers. According to Scott it pushes off the land and advancing on the sea covers the latter over vast stretches with a floating field of ice, known as the 'Great Ice Barrier,' from whose front, by their breaking off, the great tabular bergs of the Antarctic Ocean are formed. Other great ice-caps similar to these have existed in the past, but have melted and disappeared. This is clearly shown by the geological work they performed, as we shall see later.

Various Features of Glaciers

Movement. — The movement of glaciers, as compared with rivers, is very slow. Their motion was not generally known until the early part of the last century when it was observed that a hut built upon one of the Alpine glaciers changed its position, and the amount of change and the rate were measured. Since then this subject has been much studied, and a great deal learned concerning the nature of the motion of ice in glacial flowage. In the Alps the glaciers have, in general, been found to move from one to three feet a day, or about from 300 to 1000 feet a year, and this may be taken as about the rate of ordinary valley glaciers. The Muir glacier at its outlet has been found to move seven or more feet a day, or at a

rate of 2500 feet per annum, while the Greenland glaciers have been measured up to 60, or even more, feet per day, but in these cases the ice of great interior areas is pushed with accelerated motion through valley openings into the sea. It has been found that the rate is influenced by several factors; thus it increases with a steeper slope and smoother bed; it is faster when the ice is thicker, and it is more rapid in summer, when it is warmer and the ice is melting, than in winter; the grade, the thickness of ice, and the temperature are thus the chief things which affect the rate of motion.

Differential Motion. — One of the most important facts which has been discovered in regard to the motion of a glacier is that it is not the same in all parts of its mass. The glacier does not move by sliding down its bed as a whole, bodily, like a cake of ice off the roof of a house. This is evident since they often move on slopes elevated only a few degrees from a level surface, and in the case of the great ice-caps the flowage probably takes place outward from the center, owing to the thickness of the accumulated ice mass as much, if not more, than from the slope of the land. It has been found by driving rows of stakes and observing their line that the center moves faster than the sides, and that the top moves faster than the bottom. It has also been observed that there is a line of swiftest motion, more sinuous than that of the valley in which the glacier lies, or that curves in its banks reflect the current back and forth, as in a river. (See page 60.) The motion of the ice is therefore *differential*, that is, some parts of the ice are moving over and past, and therefore faster than, other parts. In these respects a glacier is like a river and the ice indeed appears to move as if it were a thickly viscous fluid, like pitch or asphalt, which, though brittle enough to be broken by a sudden blow, yields under the pressure of its own weight and undergoes slow flowage.

Origin of Glacier Motion. — The behavior of ice in exhibiting flowage in glaciers has been the subject of much investigation and discussion. It is clear that the force which causes it is the weight of the ice, due to gravity, and this vertical downward force may be resolved into components, one of which tends to thrust the ice in the direction of the slope on which it lies. It is also clear from the differential motion that the ice is not sufficiently rigid to resist this thrust, but is plastic in response to it, moving over itself, and dragging the whole mass downward. It is also known that glacial ice has a granular structure, consisting of interlocked crystal grains, which may be as large as peas or larger, and is thus similar in its texture to granite, or some other similar rock.

Let *ABCD*, in Fig. 100, be a portion of a glacier resting on the slope *CD*. Let the vertical line *gr* in its direction and length represent the force of gravity acting on it. Draw *gt* and *sr* perpendicular to *CD* and *AB*. In the parallelogram of forces *srgt* the component *gs* represents that portion of the force of gravity which thrusts the ice in the direction *BA*. The resistance to this force is composed of the friction on the bed *CD* and the backward thrust of any surface *AC*. If a mass *ABE* were entirely composed of ice resting on a level surface *AE*, the

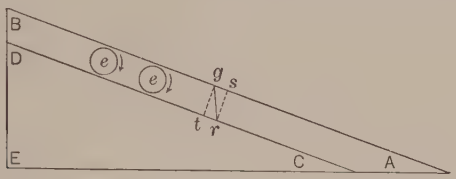


Fig. 100. — Diagram to show force causing glacial motion.

tendency of a particular layer *ABCD* to move in the direction *BA* in response to the thrust *gs* would be opposed by the resistance to shearing along the line *CD*. The differential motion which occurs shows that this resistance is not sufficient to withstand the thrust. Since the ice is composed of grains, these grains tend to revolve as shown in the diagram, *e* and *e;* this tendency is resisted by the irregular interlocked form of the grains and the rigidity of the crystal ice composing them.

It was formerly thought that ice was a viscous substance, and that when in mass it exhibited the property of slowly yielding to its weight and of flowing, that such bodies possess, as seen in pitch and asphalt. This apparent behavior of the ice in a glacier has been mentioned previously. We now know that however much ice may apparently show this property, it is not, and cannot be, truly viscous and that the apparent viscosity must be explained in some other way.

The difficulty in entertaining this view of viscosity is that ice is crystalline in structure, and in crystals the physical molecules are arranged in definite geometrical positions in space with respect to one another, and to break up this arrangement would destroy the physical identity of the substance, as when ice changes to water. In a viscous substance the molecules on the contrary have no definite arrangement and can occupy any position with respect to one another without destroying its physical state. This is a fundamental property of liquids, and viscous substances may be regarded as very stiff liquids. Cold molasses is a good example of a viscous fluid. Hence ice, being crystalline, cannot exhibit the property of true viscosity.

A variety of different theories have been proposed to explain the apparent viscosity of ice and glacial motion, which it would be beyond the scope of this work to discuss. We must, therefore, content ourselves with what, in the light of our present knowledge, seems the most probable explanation. This depends on two properties of

ice; first, that ice below the freezing point if subjected to sufficient pressure will melt and, if the pressure is removed, will refreeze; and second, that in a certain direction one part of an ice crystal can be pushed over another part of the crystal, or glided over itself, by a shearing force, without destroying its crystalline nature.

With regard to the first, the freezing point of water is lowered by pressure. This depends on the fact that water expands in changing to ice. Thus under atmospheric pressure water freezes at 32° F.; if we put sufficient pressure upon it the temperature may be lowered to 30° and since it cannot expand into ice, it will still remain liquid; should the pressure be removed it will at once freeze. Conversely if we place ice under sufficient pressure at a given temperature, say 31° F., it will contract by turning into water; if the pressure be relieved it will immediately revert to ice. At the bottom of 5000 feet of ice the melting temperature is about 30.2° F., or − 1° C.

With regard to the second property it has been found by experiment that ice crystals have the quality, when subjected to a sufficient shearing force in a certain direction, as along the plane *CD* in the crystal *ABEF*, Fig. 101, of the molecules being able to slip or *glide* along this plane and change position without destroying the physical condition, or cleaving or breaking of the ice. Thus the part *GB'HE'* in Fig. 101, illustrating the molecular structure, is as firm and

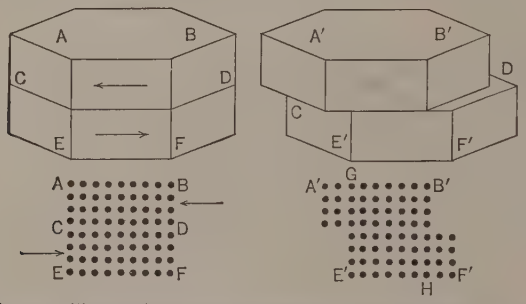


Fig. 101. — Diagram illustrating gliding planes in an ice crystal. The lower figures illustrate the molecular structure in a vertical plane.

solid an ice crystal as before. This slipping can take place between any layer of molecules in a plane parallel to the base of the hexagonal prism, but not in any other direction. Thus *A'F'* represents a crystal partly thus deformed. A crystal which has this property is said to have *gliding planes*, and it is possessed by various substances, such as the common mineral calcite, $CaCO_3$.

In applying these properties to explain glacial movement we can see that the resistance to revolution, which, by the thrust of gravity, would generate forward motion of the interlocked crystal grains of ice, as a mass of shot would flow down an inclined trough, may be overcome by the pressure. The minute points of resistance on each grain may be momentarily liquefied by the pressure, aided by the heat of friction, the grain revolved more or less and changed in

position, and, the stress being relieved, the water would immediately resolidify. And whenever a grain happens to be in the right position, so that the thrust is in the direction of the gliding planes, motion will take place along them also. Since the latter is the easier way of relieving stress, whenever a grain comes into this position it is likely to stay there, and hence in the lower part of the glacier, and towards its end, the crystals are largely in parallel position and the movement is chiefly along gliding planes. Thus by a combination of melting and refreezing under pressure, and by slippage along gliding planes, the granules are able to change position and the ice to thus undergo a slow flowage which simulates a viscous motion.

Surface of a Glacier. — The surface of a glacier is not ordinarily smooth and unbroken like that of a frozen river; on the contrary it usually has a variety of features which make travel over it extremely

Fig. 102. — Erratic block mounted on ice pedestal; caused by differential melting. Switzerland.

difficult. Aside from minor irregularities produced in a variety of ways by unequal melting, one phase of which is illustrated in Fig. 102, the ice is traversed by wide and deep cracks called *crevasses* and covered in places by accumulated heaps of earth and stones termed *moraines*. Each of these deserves consideration.

Crevasses. — These fissures may have any width, up to 20 feet or even more, and of great depth, 100 feet or greater. The most prominent ones are *transverse* to the course of the glacier and are caused by the passage of the ice stream over a salient angle in its

bed, with change from a lesser to a greater gradient, as illustrated in Fig. 103. When the ice passes over such a prominence tension is produced, greater in the upper than in the lower layers of ice; the latter yields to the tension and cracks and the fissures yawn widely at the top and gradually close below. They also curve downstream, since the motion is swifter in the center, and this tends to bend them. Even a change of angle in the bed of only two or three degrees produces crevasses, a striking proof that ice is not a truly viscous substance. Where a very steep gradient is encountered the ice is much broken and an *ice-fall* is produced, as illustrated in Fig. 107 of the Rhone glacier. The pointed jagged masses of ice made by crevassing are called *seracs*. Crevasses also occur on the margin where the ice drags against the inequalities of the side walls of the valley. These *marginal* crevasses point inward and upward at about 45° with respect to the course of the glacier. *Longitudinal* ones also occur in the terminal lobe of the glacier where the ice, relieved from transverse pressure, tends through lateral spreading to fall apart, as illustrated in Fig. 107. The first crevasse which forms in the névé field, and which shows the initiation of movement, is called the bergschrund, as previously mentioned, page 113. The transverse crevasses once formed do not remain indefinitely, for on moving over a salient angle the ice generally passes into a re-entrant one, as illustrated in Fig. 103, the tension is replaced by compression, which closes the fissures, the ice blocks refreeze, and the crevasse is obliterated. Thus the glacier in its course is subjected in places to crevassing which may disappear elsewhere, somewhat as a river at its rapids may display foamy water, not elsewhere seen.

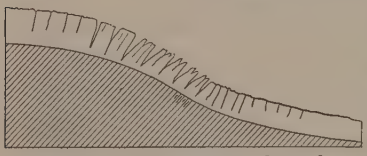


Fig. 103. — Diagram to show the formation of crevasses.

Moraines. — In an ordinary valley the débris of earth and stones, which is produced as a result of the weathering and erosion of its sides and walls, would form slopes and talus slides, which passing downward by creeping would be ground up by the stream and borne away. In a valley more or less filled by a glacier this material descends instead upon the ice and is taken along by it as bands of heaped up material. Sometimes, however, it falls into the bergschrund and, becoming frozen into the ice, is carried away. Moreover, the ice at the bottom of the névé fields being frozen into cracks and cavities and around projections in its stony bed, when motion begins, "plucks" or quarries masses of rock and takes them forward with it. All the material thus obtained and transported by

the glacier serves to form the moraines. If the material is carried on top of the ice it is spoken of as *superglacial;* if frozen fast within the ice, as *englacial;* if transported fixed in the bottom of the glacier, as *subglacial.* In the upper névé fields, since these are covered by successive snowfalls, there is little superglacial material; in the lower part of the glacier proper, as melting and waste become more and more pronounced, a greater and greater quantity of englacial material appears at the surface and becomes superglacial.

Moraines are generally divided into four classes, according to the position they occupy with respect to the glacier, as *lateral, medial, ground,* and *terminal. Lateral moraines* are formed along the sides as explained above. They become larger and more evident toward the terminus, forming ridges of earth and stones 25, 50, or even 100 feet high. The *medial moraines* are made of the lateral ones when tributaries come in, as illustrated in Fig. 104, and they may be seen in the view, Fig. 97. There may be as many as eight or ten of them. At the lower end, through melting, as mentioned above, englacial material appears at the surface and gives rise to new medial moraines. See Fig. 104. The *ground moraine* consists of the débris carried along at the bottom of the glacier. All of the material transported by the ice is eventually dumped at its end in a confused mass of earth and stones which forms the *terminal moraine.* This may coalesce with the lateral moraines as indicated in Fig. 104. Finally it must be remembered that through the longer part of its course the greater part of the material is in and under the ice.

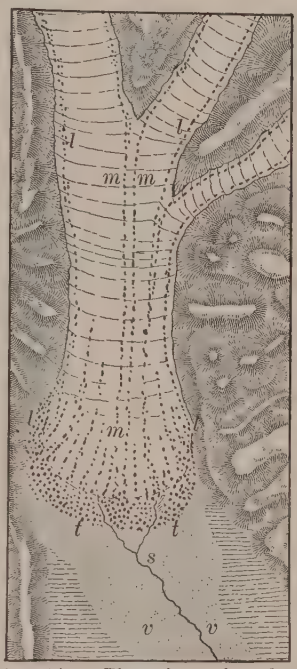


Fig. 104. — Plan of a valley glacier, showing tributaries and terminal lobe; *ll*, lateral moraines running into *tt*, the terminal moraine; *mm*, medial moraines. As melting progresses more and more material appears; *S*, exit of subglacial stream; *vv*, valley train of water-laid débris.

Veins and Layers. — The ice of glaciers frequently has a veined, or marbled, appearance due to bands of ice varying in color from blue to white. The white ice is full of minute air bubbles which produce the color; the blue is free from them. The veining is formed at places of greatest compression, as where the ice moves into a re-

entrant angle in its bed, and the pressure squeezes the air out of the white vesicular ice, turning it into blue, which the onward motion streaks out.

In the lower part, where the thrust from gravity is most pronounced, the ice often shears and is pushed over itself, forming a series of distinct layers, or bands. This banded appearance is often greatly enhanced by layers filled with dirt and gravel, which contrast with others of clearer ice. This often gives the glacier a resemblance to beds of stratified rock, as illustrated in Fig. 105.

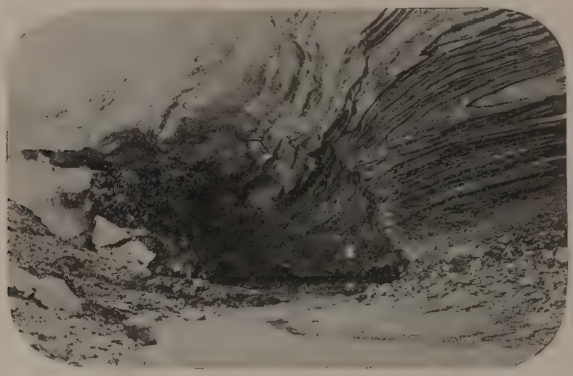


Fig. 105. — View illustrating the veined structure of a glacier, simulating folded rock strata. The situation is at the end of the glacier and the subglacial stream may be seen appearing and also morainal material. Greenland. W. H. Brewer.

Drainage; Subglacial Stream. — Within a glacier, in the region above snow-line where it is growing, the temperature must be below the melting point; in the lower part, where it is wasting, at the melting point. Hence melting is generally going on all the time; in summer it is melting rapidly at the surface, and is traversed by streams of water, which fall into crevasses, or form pools on its surface. All of this water eventually descends to form a stream under the glacier, which issues at its lower end, sometimes from an ice-cave, sometimes from along one side, which thus carries off the general drainage of the valley, Fig. 106. Such streams are very turbid, being heavily charged with sediment, and as this sediment consists of fine particles of fresh, unweathered rock, ground up by the glacier on its bed, they are chiefly white in color and give the stream a peculiar milky appearance, which it may retain for long distances. This milky look is so characteristic as to lead to the suspicion, when seen in a river, that it is fed by melting glaciers higher up in its course.

Advance and Recession of Glaciers. — We know in a variety of ways that great changes of climate have occurred in the past, as will be fully discussed in the historical part of this book. These changes have been not only general, but also local, as affecting some

Fig. 106. — Subglacial stream and ice-cave. Morainal material is seen above which falls as the ice melts and helps to build the terminal moraine. Transported blocks fill the bed of the turbulent stream which carries the finer earth and ground-up rock away. Chamounix, Switzerland.

particular region, and have already been mentioned in one aspect under the history of salt lakes. Such changes have a profound effect upon the existence of glaciers. Thus we know from evidence, to be shown later, that in recent geological times North America and Europe were covered with great continental glaciers, or ice-caps, similar to that of Greenland to-day, as far south as Ohio and middle Germany. At the same time the valley glaciers of the Rocky Mountains and of the Alps had a vast extension over their present size. With change of climate these ice-caps have disappeared, and valley glaciers have in some places greatly shrunken and in others melted away.

But aside from these great changes, occupying periods of geologic time, glaciers appear to grow and advance, or to diminish and retreat, in response to varying climatic cycles of years of greater precipitation and coldness, compared with ones of greater sunshine and warmth. Thus the glaciers of the Alps, during the past century, have been observed in a number of cases to have experienced such

oscillations, but up to the present an insufficient amount of accurate data, relating to this phenomenon, has been gathered to enable us to state definitely the periods, and the laws governing them, and whether on the whole, irrespective of these periodic oscillations, glaciers the world over are diminishing or not. At the present time, in the Alps and in North America, they are in general retreating, as illustrated in Fig. 107 of the Rhone glacier. The Muir glacier in Alaska has retreated several miles from the position it was observed to have in 1887 (in this case probably due in large part to shattering from a heavy earthquake) and the Illecillewat glacier, one of the valley type in British Columbia, at least 500 feet in the same time. Some individual glaciers in the Alps and in Alaska have, on the other hand, been observed to be advancing.

Fig. 107. — Two views of the Rhone glacier, Switzerland; the upper one taken in 1870, the lower in 1905, which illustrate the retreat of the ice in 35 years. The older one shows the terminal lobe and longitudinal crevasses.

Geological Work of Glaciers

The work of glaciers, like that of rivers, consists in *erosion*, *transportation* and *deposition*. While in these features, speaking broadly, they are like rivers, the manner in which the work is done and the results achieved are very different, as will appear from the following discussion of them. Our knowledge in this case is obtained by observation of living glaciers, of areas which they have uncovered and abandoned in recent retreats, and by application of the facts thus learned to regions in which they no longer exist but which these evidences show they once occupied.

Glacial Erosion. — In its highest part, under and at the edges of the névé slopes, a glacier erodes chiefly by "plucking" and gathers its load by this process and by collecting the débris coming to it

through the weathering of the slopes above the snow, as described under moraines. The work of gathering is especially active in the bergschrund, where this crevasse comes between rock and snow; in summer time thawing takes place during the day, the rocks are wet, and freezing is apt to occur at night, springing out blocks which fall down to be enveloped by the ice and carried away. Thus, over the area where the névé fields rest, they are constantly quarrying inward and downward, and in the long course of time this gives rise to partly bowl-shaped valleys, or basins, called *amphitheaters*, or *cirques*. These cirques are often cut somewhat deeper at the center than at the place of discharge and thus, when the valley is no longer filled with ice and snow, these depressions are occupied by one or more small ponds or lakes, as shown in Fig. 108. Such cirques are common features in the mountains

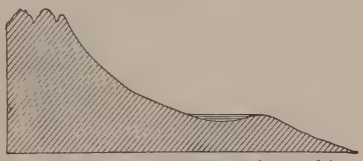


Fig. 108. — Section through amphitheater and glacial lake.

Fig. 109. — View of glacial cirque or amphitheater. Sultan Mountain, Colo. F. L. Ransome, U. S. Geol. Surv.

of northern regions and exhibit the collecting basins of former glaciers. See Fig. 109.

As soon as movement begins the erosion is somewhat different. Plucking continues, but in addition the earth and stones frozen fast

into the bottom of the ice form a huge rasp, whose power is enormously augmented by the great weight of ice above. Thus in its moving course the glacier is constantly grinding away the rock-bed on which it rests. This grinding occurs not only over the bottom of the bed, but along the sides of the glacier-filled valley as well, making a glacier, therefore, differ very markedly in erosion work from a river, as we shall presently see. The effectiveness of this engine of erosion depends largely on the rigidity with which the rocks and gravel, the teeth of the rasp, are held by the ice, and thus on the temperature; at the lower end when the ice is soft and melting it has been observed pushing over morainal material without disturbing it and this has sometimes given a wrong impression that glaciers are not very efficacious agents of erosion.

Glaciation. — The result of this work is seen on bed-rock which is smoothed, rounded and polished as it is ground away, as in Fig. 110, and scored with scratches and grooves, called *glacial striæ*,

Fig. 110. — Glaciated country rock, Eastport, Maine.

running in the direction of glacial flow. See Fig. 111. These are made by pebbles, sand, etc., held firmly frozen in the ice. They may be very fine scratches or attain the dimensions of small channels, sometimes beautifully fluted. Projecting masses or hummocks of bed-rock, instead of showing angular, broken outcrops, are more or less smooth and rounded, often shaped like the half of an egg, and these features are called *roches moutonnées*, a term adopted from the Swiss mountaineers in allusion to a fancied resemblance to the backs of a flock of sheep. Small lakes or pools may occupy rock-basins where depressions have been ground out of bed-rock. The process of producing such characteristic features is called *glaciation*, and a country which exhibits them is said to have been *glaciated;* they are seen when glaciers have retreated, or disappeared, and by their

presence we are able to recognize the former existence of such glaciers, in regions where these have long since vanished, as in New England, for example.

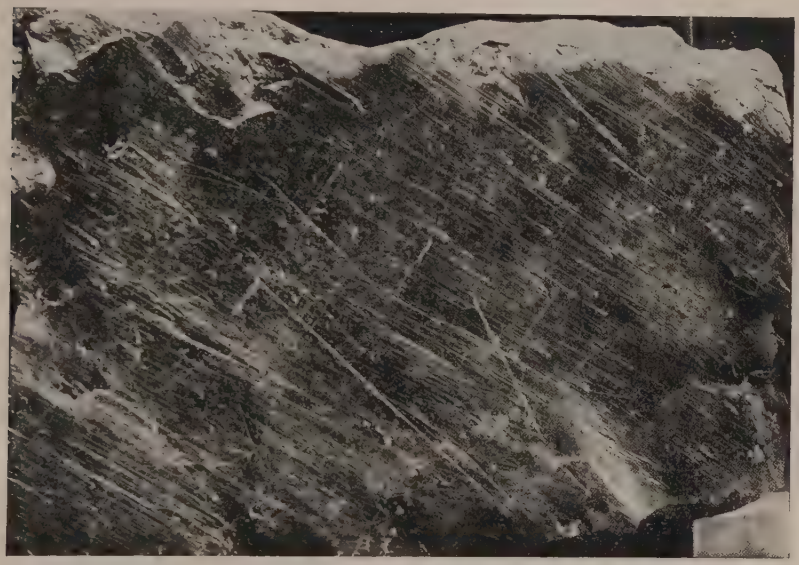


Fig. 111. — Glacial striæ; scratches and groovings made by moving ice on limestone bed-rock. Near Rochester, N. Y.

Glacial Valleys. — The effects of glacial erosion are seen, not only in the smaller details mentioned above, but also in larger features, such as affect the topography of valleys. The normal shape of a river valley produced by corrosion and weathering, has been discussed on page 46 and shown to be that of a V in section. In a valley more or less filled with ice the longitudinal erosion takes place, not only on the bottom, but also along the sides and hence a well glaciated valley has normally a U shape in cross section, as seen in Fig. 112. In a river valley the tributaries and the ravines they have made normally join the main stream and its valley bottom at grade; in a glaciated valley the tributary

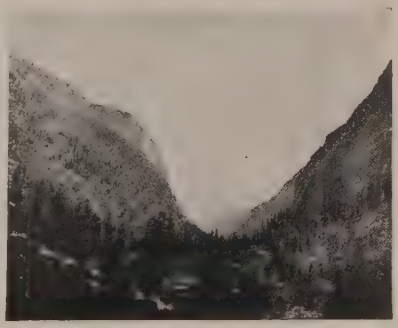


Fig. 112. — Characteristic U shape of glacial valley. Kern Valley, Cal. H. Gannett, U. S. Geol. Surv.

glaciers cannot cut as fast as the main one, and the mouths of their valleys are ground back, and end high up on the wall of the main valley into which they discharge in cascades. Such *hanging valleys*, as they are called, with their water falls are common features in the scenery of the northern Rocky Mountains, in Switzerland, and in Norway, and are illustrated in Fig. 113.

Fig. 113. — A hanging valley and falls. Yoho Valley, Brit. Col.

In a river valley the spurs between ravines run down and die out at, or near, the river; in a glaciated valley, these are ground away by the longitudinal erosion up to the level of the ice and after its recession terminate in more or less well defined inverted V shapes in the wall of the main valley; these spurs are said to be *facetted*. Thus U-shaped sections, hanging tributary valleys, and facetted spurs are characteristic features of the topography of glacial valleys. The change of a

Fig. 114. — A mountain mass, normally eroded by weathering and running water and unaffected by glacial action. The valleys and ravines are V-shaped in section. W. M. Davis.

normal river valley into a glaciated one exhibiting them, by ice invasion and retreat, due to climatic changes, is seen in Figs. 114, 115 and 116.

Fig. 115. — The same mass as in Fig. 114 strongly affected by glaciers which occupy the valleys. The rugged topography above the ice, produced by weathering and frost should be noted. W. M. Davis.

Fig. 116. — The same mass of mountains as in Fig. 115 after the retreat and melting of the ice. Note the nature of the topography, the amphitheaters, some with lakes, the hanging valleys and the facetted spurs. W. M. Davis.

Glaciation by Ice-Caps. — In the great continental ice-caps the ice appears to move *en masse* over broad areas away from the general center of dispersion and regardless of the minor features of underlying topography. Hence on their retreat we find the glacial striæ, which indicate the direction of flow, pointing in the same way over wide areas, and down, up, and across valleys. However, it has been noticed that valleys running somewhat in the general trend of flowage, have in places exercised some control and given rise to local sub-currents in the ice. Where the ice-caps end in mountain ranges and push down their valleys in projecting tongues to the lowlands, or the sea, they exhibit the erosional features common to valley glaciers. Striated and polished bed-rock, roches moutonnées, and rock-basin lakelets over wide stretches of country are the characteristic features of glaciation by the continental ice sheets.

Glacial Transportation. — There are no special problems connected with transport by ice, as compared with water. Whatever lies upon it, or is enveloped in it, regardless of size is irresistibly borne along, and eventually deposited when the ice melts.

Glacial Deposits

Moraines. — The manner in which these are formed has been already described. As seen at the terminus of a glacier, or after its retreat, they consist of mingled heaps of earth and stones, sometimes several hundred, or, in exceptional cases, 1000 feet high, or even more, and wide in proportion. Unlike water-laid material, which is nicely assorted as to size and deposited in stratified layers, they consist of confused débris of all sizes tumbled together, as illustrated in Fig. 117, and this want of stratification is one of their distinguishing characteristics. Those pieces of stone, which have been transported as sub-glacial material and have taken part in the erosive work of the glacier, have smooth, flat surfaces, or *facets*, ground upon them and are polished and striated, or scratched. In other words, they are *glaciated*, and such facetted, glaciated pebbles are characteristic features of glacial work, and of their moraines. On the other hand, the pieces of rock brought down on, or in, the ice, not being subjected to grinding, are as rough and angular, as when removed from the valley walls, and like those of any talus. The heterogeneous material forming the moraines is known as *glacial till*, or *bowlder clay*.

Since at its lower end the ice moves not only down but radially outward, as illustrated in Fig. 104, the terminal part of the lateral moraines may be so greatly increased by this movement that they may become of huge size; as the glacier

retreats they continue to be left behind, or to grow, following after it. Thus they may be very large, while the terminal portion in front of the ice, may be relatively small, or almost wanting. They are really laterally terminal moraines.

Glacial Bowlders or Erratics. — Another characteristic feature of a country which has been glaciated is the presence upon it of scat-

Fig. 117. — Glacial till or bowlder clay, consisting of the unassorted material of the moraine. The Caucasus.

tered bowlders of all sizes and shapes which are different in nature from the underlying bed-rock. They are transported blocks of rock which have been left from the melting of the ice; that they have been transported is proved by the difference between them and bed-rock. They are called *erratics* or *glacial bowlders*. They are not infrequently of great size, as large as a small house, as illustrated in Fig. 118. In some cases, through the gentle lowering by the melting of the ice they have been deposited in very insecure positions and are known as *perched blocks;* they may be even so nicely poised that although of large size they may be rocked by pressure of the hand, and are known as rocking stones. Such deposition would be impossible by water and, in general, indicates the agency of ice, though they may sometimes be bowlders of disintegration, page 28.

Through peculiarities in the character of the stone, such erratic blocks have often been traced many miles, 50–100, or even more, to their parent ledges of bed-rock. The most striking instances of transported bowlders are those left by former ice-caps. In general the northern parts of North America and Europe

are more or less covered with them. If they can be traced to the parent ledges, as in the case of the "bowlder train" of Richmond, Mass., they afford valuable indications of the direction of flowage, and confirm the indications left by the striæ on bed-rock.

Glacial Lakes. — In a country which has been recently glaciated, lakes are a common feature. The formation of small rock-basin

Fig. 118. — Glacial erratic; a transported bowlder of trap resting on sandstone; weight about 500 tons. New Haven, Conn.

lakes by irregular erosion of bed-rock by glaciers has been mentioned already. But a much more important way in which glaciers form lakes is by moraines left athwart valleys, which make dams, ponding back the drainage. Of the many beautiful lakes which lend charm to the scenery of the hilly and mountainous regions of North America and Europe, in the Adirondacks, in New Hampshire, Maine, Canada, the Alps and Norway, by far the greater part have been made in this way, see Fig. 119. These dams have mostly been left in valleys on the retreat of the continental ice-caps. In the Southern States which have been unvisited by the ice lakes are rare, or wanting, as previously mentioned, page 74.

In some of the Northwestern States and Canada, as in Minnesota for example, the many small lakes are due, not to the damming of definite valleys, but to the filling with water of depressions in the irregular hummocky, ridgy surface of the wide sheet of morainal débris left on the retreat of the ice-cap.

Thus glacial lakes are due to rock-basins, morainal dams in valleys, and to hollows in morainal deposits.

Ice-Cap Deposits; Glacial Drift. — The deposits left by the continental ice sheets, or caps, are somewhat different from those of valley glaciers. As they have no side boundaries there are no distinct lateral moraines but only the terminal one. The former edge of the ice is marked by this terminal moraine, a deposit of till crossing the country as a series of hills, hummocks, knobs, and ridges,

Fig. 119. — Lake due to glacial action. The topography in the background shows the characteristic forms and surfaces of glaciation. Sierra Nevada, Cal.

with depressions between called "*kettles*" which are often filled with water. As the ice continued to retreat by melting, the material it contained was left as a broad sheet of till, or bowlder clay, covering the country. As the retreat apparently takes place irregularly, with oscillations of advance and recession, like those observed in modern glaciers, such stages are marked by new terminal moraines, which, as they lie back of the most advanced one, have been called *recessional.* Certain peculiar forms of these glacial deposits have been called *drumlins;* they consist of rounded, elongated hills, or short ridges, of unassorted till whose longer axis points in the direction of ice movement; it is not definitely known how the deposits assumed this form and position. They are especially common in central New York and in eastern Wisconsin, and are illustrated in Fig. 120. All the material, the sheets of till, the moraines, erratic blocks, etc., whose deposit on glaciated bed-rock, whose want of gradual transition into country rock, observed where soil is found in place, and foreign nature prove it to have been transported, and whose hetero-

geneous, unassorted character and glaciated pebbles show it was deposited by ice, is known under the general term of the *glacial drift.* This term is also applied to these materials where they have been transported or washed and laid down by water; in this case strati-

Fig. 120. — Drumlin near Newark, N. Y. G. K. Gilbert, U. S. Geol. Surv.

fication is more or less distinctly shown in the deposits and they are commonly referred to as "modified" or "stratified" drift. These we will now consider.

Fluvio-Glacial Deposits. — The melting of the ice of glaciers and the natural drainage of the valleys occupied by them produce streams heavily charged with sediment as described on page 126. As the grade lessens, the streams, unable to carry this material, deposit it on the valley floors building up temporary baselevels, or river flats, in which they wander in devious and shifting channels. As the streams are heavily burdened they become graded on definite slopes and this deposit running downward along the bottom from the terminal moraine is known as the *valley train.* In the case of continental ice-caps the washed down material, instead of being concentrated, as in a valley train, may be spread widely by meandering streams over broad areas, giving rise to what are known as *outwash plains,* or *frontal aprons.* Such deposits, since they are laid by water, are more or less distinctly stratified, while the pebbles of the gravels through attrition may become rounded and lose more or less completely the facets and scratches they may exhibit in the moraines. Fig. 121 shows a section of this water-laid drift resting on unassorted till.

In the outwash plains conical depressions, sometimes 100 feet deep, are found which are called *kettles*. They are well illustrated in the sand plain above New Haven, Conn. They are supposed to have been formed by the crumbling of cavities made by the melting of isolated blocks of ice, left for a time by the retreat of the irregular glacial front, and then surrounded and more or less covered by sediment from the glacial streams.

Fig. 121. — Water-laid glacial drift on unassorted till. Columbus, Ohio.

Kames and Eskers. — These are peculiar forms of deposit made by the sediment-laden streams from the ice caps. *Kames* are hills, knobs, or short ridges, sometimes attaining a height of 100 feet, which resemble drumlins, but differ from them in that they consist of stratified material and, instead of pointing in the direction of ice flow, they tend to arrange themselves athwart it. They are apt to occur in groups with depressions between which sometimes contain water. They are thought to represent depressions in the irregular front of the ice sheet which have been filled with sediments and left as projections upon its melting.

Eskers are long winding ridges of stratified sands and gravel, 10, 20, or even 100 feet high, with very even and narrow crests and trending in the general direction of ice flow. They may strikingly resemble artificial railway embankments. While found in various parts of the Northern States they are particularly striking in Maine. They have a great development in Scandinavia where they run across country, in some cases, for many miles. They are illustrated in Fig. 122. It is supposed that they have been built by streams which had cut channels for themselves in and under the ice. The deposit would be confined by the ice walls and upon the melting and retreat of the ice sheet would be left as a sinuous ridge, marking the

former channel. They might then be described as a confined, retreating delta or alluvial fan.

Fig. 122. — The esker of Punkaharju, Puruvesi, Finland. In Scandinavia such a ridge is called an 'ose,' plural 'osar.'

With respect to the deposits made and left by ice-caps the following table will enable the student to summarize the main features brought out in the above discussion.

Ice-laid, heaped

Moraines. Irregular ridges, when terminal, traverse to ice flow.
Drumlins. Ovate hills, elongate parallel to ice flow.

Water-laid, stratified

Kames. Round to ovate hills grouped transverse to ice flow.
Eskers. Winding, very elongate, often parallel to ice flow.
Frontal aprons. Outwash plains beyond morainal deposits.

Icebergs

Icebergs are formed in northern regions where glaciers come down from the land and enter the sea. Pushing out into the water the buouyancy of the ice, aided by the lifting action of the tides, floats the end of the glacier and causes huge masses to break away, which float off as icebergs. The process is illustrated in Fig. 123.

Icebergs are sometimes of very great dimensions, rising 200 feet or more above the sea, though this is uncommon. The specific gravity of solid ice is about 0.9, compared with water, but glacier ice is more or less porous, and perhaps as much as one-seventh of the mass of a berg may be above water. Thus they may extend downward 1500 feet; they have been observed aground in

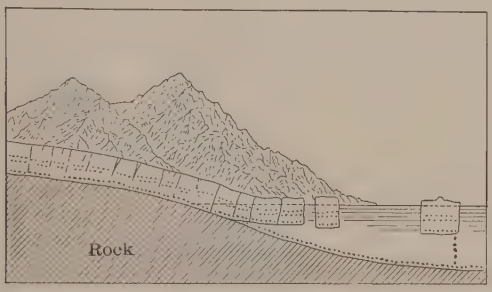


Fig. 123. — Diagram illustrating the formation of icebergs.

water of this depth. The volume of some bergs has been estimated to be as much as 500,000,000 cubic yards which would cover an area of one mile square 500 feet deep. The largest bergs are those which break from the great ice barrier surrounding the Antarctic continent (see page 119); they are often remark-

Fig. 124. — Icebergs in the Polar sea. Only a small part of the berg is above water, but this may be the longest, thinnest part of the mass which projects like the apex of a floating cone. It is surrounded by floes of frozen sea-water.

ably tabular in form. The source of the North Atlantic bergs is chiefly the great ice-cap of Greenland, especially that prolongation of it into the sea known as the Humboldt glacier, which presents an ice-front, or cliff, 60 miles long. It should be remembered that icebergs are always composed of *fresh-water ice* and

are made on the *land* by glaciers, the ice of the frozen sea itself forms ice-fields, called *floes*, which are not originally more than 8–10 feet thick, though by pressure, crowding, and over-riding, they may in places become several times this thickness.

By the general circulation of oceanic waters which has been previously described, all the floating ice of high latitudes in both hemispheres is gradually drifted into warmer seas, northward and southward respectively towards the equator, and eventually melted. In the North Atlantic the bergs may be floated as far south as 40°, making a formidable menace to navigation. Were it not for this general law ice would accumulate indefinitely in polar regions until the greater part of the waters of the world were locked up in polar ice-caps, while the lands would be arid deserts.

Geological Work of Floating Ice. — In high latitudes the floating ice of the bergs and floes, driven against the shore by winds and tidal currents, chafes against the rocks, eroding and polishing them. Icebergs grinding on the bottom may also erode and scratch the rocks, but such effects are probably relatively small in amount. Icebergs, like other glacial ice, may contain englacial material, earth and bowlders frozen in the mass, which is dropped on the bottom as the berg melts. While locally such deposits must be slight, in sum total the amount of material transported in this way must be large. Since the North Atlantic bergs are apt to go aground in the shallow water southeast of Newfoundland and melt, it has been supposed that the Grand Banks have been largely formed in this way, but there is no direct evidence of this and a rough estimate of the quantities of material, the number of bergs, and the time required to form them makes it extremely improbable.

CHAPTER VI

UNDERGROUND WATER

The various agencies which have been described as operating upon the surface of the earth, that is the atmosphere and the watery envelope of the globe in its varied forms of running water, the ocean, lakes, and snow and ice, all tend to cut away its irregularities and to furnish material which is used in filling up depressions. Hence they tend in the long course of time to make its surface smoother and are therefore spoken of as *levelling* agencies. But water in addition to this work of levelling, which is largely mechanical in its nature, performs other geological work of vast importance and chiefly in a chemical way. One phase of this chemical work has been already discussed in connection with the formation of soil, page 22, and another has been alluded to in relation to that part of a river's burden which is carried in solution. But the matter as a whole is best understood through a discussion of the nature of underground water and the functions it performs.

Underground Water. — It has been previously stated that of the water that falls in rain one part is evaporated and goes back into the air, that another portion passes directly over the surface into the sea, while a third portion sinks into the soil, and into the cracked and broken bed-rock below it. It is this last part of the rainfall, which thus sinks downward, that we know as *underground water*. Various things may happen to it; it may find its way to the surface as springs and aid in the general run-off; it may be drawn to the surface by capillary attraction through the pores in the soil and be evaporated; it may be sucked up by plants and evaporated through their leaves; it may never return to the surface, but find its way into the sea by underground channels; it may remain held, for aught we may know, for indefinite periods in deep fissures in the rocks, and lastly it may enter into chemical combinations with the minerals of the rocks and become fixed. Before studying the geological side of these happenings certain features of underground water should be explained.

Situation of Underground Water. — The water that percolates downward fills the fissures in the rocks and the interspaces, or pores, between the grains of overlying soil up to a certain level. Above

this level the soil may be moist but the pores are not filled; below it the soil is saturated, consisting of a mixture of soil grains and water, like sand and water in a basin, and thus forming, so to speak, an underground lake. The surface, or upper level, of this underground water is called the *water-table* and it is this water-table that one endeavors to reach and penetrate in ordinary dug wells. The depth of the water-table below the surface of the ground varies in a given locality in response to wet or dry seasons; in different localities according to circumstances, especially the annual rainfall. Thus in very humid regions it is generally but a few feet below the surface, while in very arid regions it may be hundreds of feet down, entirely below the soil and in the rocks beneath. The depth to which underground water may penetrate in the rocks is unknown, but experience in deep mines seems to show that it is not very far, and it must in any case cease at the point where, through the pressure of the

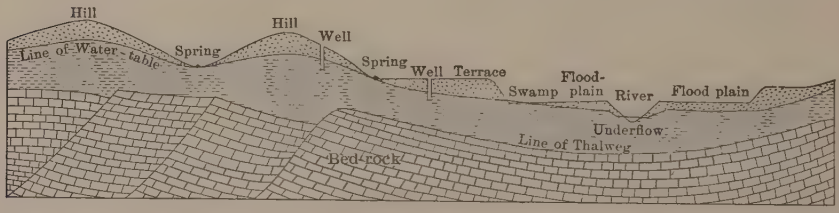


Fig. 125. — Ideal section across a river valley, showing position of underground water, its relation to bed-rock below, and the contour of the water-table with reference to that of the ground above. Vertical scale exaggerated. (After Slichter.)

superincumbent masses above, cracks and fissures in the underlying rock can no longer exist. This occurs, however, at a number of miles below the surface, since it has been demonstrated by Adams that cavities can remain open to a depth of at least 11 miles. Beyond this it may be that, in response to the pressure, all rocks, however rigid they may appear at the surface, are weaker than the pressure upon them and, yielding like metals under the stamping of a die, all cavities in them may be closed up.

Contour of the Water Table. — The contour of the water-table in a general way follows that of the ground above, rising under hills and sinking in valleys, as illustrated in Fig. 125. If the surface of the ground intercepts the water-table then the underground water appears, and if this occurs on a hillside a spring results, while, if the surface of the ground and the water-table coincide for a distance, this area is a swamp or bog. In lakes and rivers the contour of the

ground sinks below that of the water-table and the latter stands revealed.

Porosity of Soil and Rocks. — The volume of space between the grains of a soil, or its porosity, which can be occupied by water, depends very much on the nature and arrangement of the particles composing it. In ordinary sand the volume of pore space is usually about 30 per cent, and may be considerably larger; in ordinary loam, which contains a good deal of clay, see page 27, it may be larger, from 40–50 per cent. Thus in a natural basin covering a certain area, in which the average depth of sandy soil is 30 feet to bed-rock, and in which the water-table stands 15 feet below the surface, the total volume of underground water would equal that of a lake covering the area and about 5 feet deep.

All rocks are in some degree porous, sandstone the most so, the volume of interspaces rising in some cases to 30 per cent in this rock, while in crystalline rocks, like granite for example, it may be only one per cent, or even less. This applies to the interspaces between the rock-grains and not, of course, to cracks or fissures which can only contain a small part of the underground water. The average pore space is probably not over 10 per cent. Assuming this amount for the surface and that it diminishes with the depth it was formerly calculated that the total quantity of water held underground in the world was as much as one-sixth that contained in the ocean, but later investigations, which show the dry nature of the rocks in very deep mines, have led to calculations which very greatly reduce this amount. But in any case the total amount is actually very great.

Motions of Underground Water. — Probably only the lower depths of underground water remain stationary for any length of time; that occupying the upper layers of rock and the soil has a slow but regular motion, depending on the difference of pressure due to gravity, from point to point. Thus it urges its way slowly onward from higher to lower levels and ultimately, like the water of the run-off, it seeks its goal in the sea. In the sands filling a valley below the bed of a river, as illustrated in Fig. 125, the water underderground is following the same course as that filling the channel above, though at a vastly slower rate. This is known as the *underflow*. The rate of movement is relatively rapid in gravels and coarse sands, much slower through finer sands, while in fine clays it is almost indefinitely slow. A familiar example of this is seen in the rapidity with which puddles in a sandy road, after a shower, drain away, while in a bed of clay they remain until evaporated. Thus clay,

and rocks composed of clay (shale), are practically impervious to the movement of water, while in sand and sandstone, on account of the porosity, it much more readily takes place. Yet even in sands the movement is very slow and a general average of the rate of underflow, as determined from experiments, is about one mile per year. The natural line of drainage over the underground surface of

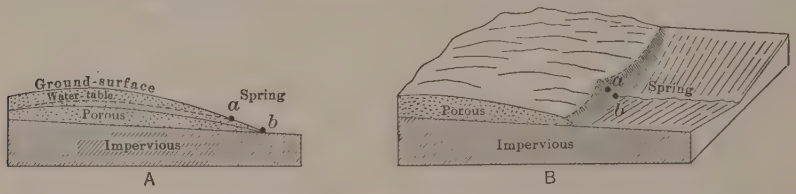


Fig. 126. — Diagrams illustrating conditions favorable for ordinary hillside springs. *A*, in section; *B* shows how the contour of the thalweg concentrates the seepage to form a spring. Dotted line, high water stage, spring at *a*; solid line, low water stage and spring at *b*.

Fig. 127. — Thousand Springs, Snake River canyon, Idaho. I. C. Russell, U. S. Geol. Surv.

bed-rock, along which the underflow takes place may be called the *underground thalweg* (German, valley way), and is illustrated in Fig. 125.

Springs. — Where the contour of the ground intercepts the water-table underground water appears at the surface. A general oozing out of the water under these conditions is known as *seepage*, but if the circumstances are such that a volume of the water is led to issue out in quantity sufficient to form a distinct current an ordinary

spring results, as illustrated in Fig. 126, *A* and *B*. Fig. 127 illustrates the cutting of the water-table by the side of a canyon and the issuance of the underground water in a series of springs.

Another type of spring is formed when the surface water enters and fills some porous, inclined layer, such as one of sand or sandstone, lying between two impervious ones, as of clay or shale. Driven onward by the weight of the column behind it the water may acquire such hydrostatic pressure that if it encounters the plane of a fissure it may be driven up along this, through suitable channelways, and issue at the surface as a spring. This is illustrated in Fig. 128. Such springs are often called *fissure springs*.

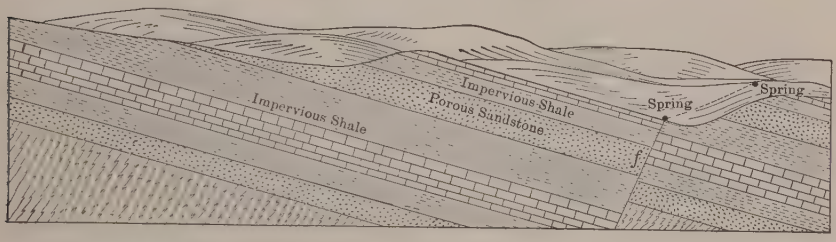


Fig. 128. — Section illustrating conditions favorable for springs, if fissures, such as *f*, are present, or for artesian wells if fissures are absent.

In such an arrangement as is postulated in the figure, along the line of intersection of the fissure with the surface, springs might be expected at various points where suitable channels for the upward flow of the water exist, as suggested in the diagram.

Such springs are usually very steady in their flow and less liable to be affected by droughts than ordinary hillside springs. While usually cold, the water may come in contact with heated rocks and issue in a warm spring. It may sometimes take up substances in solution and give rise to a *mineral spring*.

The condition under which porous beds become filled with water is important, not only for fissure springs, but also for artesian wells, described below. It is illustrated in Fig. 129. The porous layers *BD* become filled, not alone by the rain which may chance to fall on their exposed surfaces and by the water which is shed upon them from the higher impervious slopes *A* and *C*, but there is also an entrance of water into them from the current of the river, concentrated from the water shed above and beyond, which, spreading out in them, furnishes a constant source of supply.

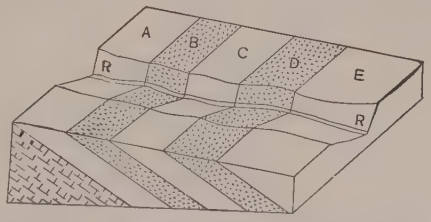


Fig. 129. — Diagram to illustrate entrance of water into porous rock layers, or strata. *ACE* impervious beds, *BD* porous ones. *R R*, course of river.

Artesian Wells. — If, under the conditions described above as producing fissure springs, where an inclined porous rock-bed between impervious ones becomes filled with water under sufficient pressure, a bore hole be put down the water will rise to the surface producing an *artesian well.* It may be regarded as an artificial fissure spring, and the arrangement illustrated in Fig. 131 is especially suitable for artesian wells. In some cases the porous layer may have the form underground of a basin, but this is not a necessary con-

Fig. 130. — Artesian well, near Provo, Utah. G. E. Richardson, U. S. Geol. Surv.

dition. The height to which the water will rise above the surface depends on the pressure, which in turn depends on the height of the water column, or "head," in the porous layer above the point of exit, as shown in the figure. An artesian well is shown in Fig. 130.

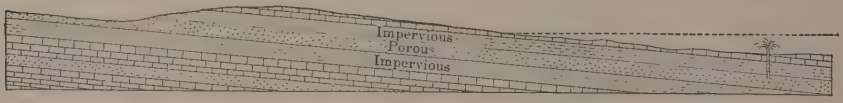


Fig. 131. — Section showing conditions favorable for an artesian well. Vertical scale exaggerated.

The terms porous and impervious used in this connection are relative ones, as all rock-beds are to some extent porous. In addition to the conditions mentioned as necessary for artesian wells, others are that there should be a rainfall

over the region where the porous layer comes to the surface sufficient to keep it filled with water, and also that the rock-beds should not be so cracked, fissured, or displaced as to permit the easy escape of the water and thus cause the loss of the required pressure. Artesian wells cannot, therefore, be made in any place by simply boring deeply enough, unless the requisite geologic conditions are present. Any well bored in rock, if it simply intercepts the level of underground water, is often called an artesian well, but this is an incorrect use of the term; there is no difference in principle between one of this kind and an ordinary dug well. Some of the most important water-bearing formations in the United States which furnish artesian wells are found in the so-called Dakota sandstone, which comes to the surface along the Rocky Mountains and underlies North and South Dakota, Kansas, Nebraska, and extends into Canada; the Potsdam sandstone which outcrops in central Wisconsin and underlies Illinois, Indiana, Iowa, and Ohio; and in the beds of sands and clays, which, beginning on Long Island, extend southward to Texas, forming the Atlantic coastal plain. In New England the conditions are unfavorable for artesian wells.

The depth to which wells must be bored in some places before artesian water is attained is very great, up to 4000 feet, examples being found in Berlin, St. Louis, and Pittsburg; those of 1000 are not uncommon, while along the Atlantic coast they are generally shallow, 100–300 feet. The volume of water may be very large, the great 12-inch well at St. Augustine, Florida, with a depth of 1400 feet supplying 10,000,000 gallons a day. Where many wells are put down close together they may interfere with each other and even lower the pressure to such an extent that the water will no longer overflow.

Geologic Work of Underground Water

Underground water is a very important geologic agent. The chief work that it does is to *take substances into solution and carry them elsewhere, often finally depositing them*, and it is, therefore, chemical in its nature. While this work may seem small, when examined in detail, the total results performed during the long period of geologic time have been enormous. In some measure this work has already been considered. Thus in the description of the decay of rocks and the formation of soil it was pointed out that certain constituents, like the alkalies in the feldspars in the rocks, went into solution and were removed. It was also shown that calcium carbonate, a common rock-making material, under the influence of water and carbon dioxide was dissolved and carried away (page 24). These actions are accomplished by atmospheric water as it passes underground, and may thus be regarded as the first stages of the work of underground water. Again its work was in some degree considered, when it was stated what a large proportion of the burden carried by rivers consisted of material in solution (page 43). This shows the removal of the substances dissolved by underground water and their ultimate goal in the sea. And again in the formation

of salt lakes, and in the deposits which occur in them (page 76), is seen this work of solution, removal, and deposit.

But while all these illustrate the general chemical work of water, partly on the surface and partly underground, there are certain features which demand particular consideration.

Solution. — The solvent action of rain-water passing into the soil and rocks is greatly increased by the substances which it may carry with it, or which it may otherwise obtain. In its passage through the air it dissolves notable quantities of carbon dioxide and oxygen, with minute amounts of other materials. See Fig. 132. In

Fig. 132. — Rock whose more soluble parts are being dissolved by the action of atmospheric waters. Wind aids the rain in removing the loosened material. Near Livingston, Mont. C. D. Walcott, U. S. Geol. Surv.

passing through the soil of humid regions it may absorb much more carbon dioxide and also organic acids produced by the decomposition of vegetable matter. In many places, particularly volcanic regions, volatile substances, especially carbon dioxide, are evolved from the depths, and may dissolve in the underground water and thus greatly augment the amount of chemical reagents present in it. All of these promote its efficiency as a solvent. In addition, as it passes into deeper zones, it may become subject to pressure, or come in contact with heated rocks and have its temperature raised, both of which largely increase its chemical activity; the amount of gases,

such as carbon dioxide, which it can dissolve and hold in solution, is, indeed, proportional to the pressure.

Pure water itself acts upon many things, but with its chemical efficiency heightened as described it attacks the mineral substances composing the rocks and soils; some of them it takes directly into solution, as, for example, gypsum, $CaSO_4 \cdot 2\,H_2O$; with many others a chemical reaction takes place with formation of new compounds, some of which are soluble and are carried away, while the insoluble ones remain. This latter process is illustrated in the breaking up and decay of feldspar, as described under the formation of soil; the alkaline carbonates produced are leached out, while the insoluble kaolin, or clay, remains.

One sees, therefore, from this that the outer portion of the earth's crust over the land surfaces is one of destruction and change. And this is not limited to the merely superficial layer, in which the rocks are changed into soil, but extends downward into the zone of cracked and fissured rock far below.

The material taken up and held in solution may pursue one of two courses, depending on what happens to the water containing it. It may work down deeply into the rocks and be there deposited, or it may pass into the drainage by leaching through the soil or by coming out in springs, and be thus carried into the ocean. The first course may be considered a little later, we are here concerned with that taken away.

Chemical Denudation. — The process by which the land surface is wasted by material going into solution and being taken into the sea is known as *chemical denudation*, to distinguish it from the mechanical wear of ordinary erosion. In the aggregate it amounts to an enormous sum each year. It has already been briefly mentioned in the discussion of a river's burden. On the basis of a large number of analyses of the waters of the Mississippi, which give the average percentage of the salts which it contains, and of the total volume of its discharge, F. W. Clarke has calculated that each year there are removed 98 tons (metric) of matter in solution per square mile over its basin. This does not mean, of course, that this amount is taken from each square mile, but is the general average; it is more in some places, in others, less. If we estimate the area of the basin in round numbers at 1,240,000 square miles this gives 121,520,000 tons per annum for the total basin. For the whole of North America the estimate is 79 tons per square mile, or 474,000,000 tons for its total area. For the whole world this estimate of 79 tons would be too high, for arid desert regions, like those of Central Asia and Africa,

have a scanty drainage and thus lose a relatively much smaller amount of mineral matter in solution. The same is true in humid tropical countries where the soil, held in place by dense vegetation, has for centuries past been leached of its soluble matter, and of Arctic ones where the drainage is largely over frozen soils which contribute very little. Taking these facts, as well as others, into consideration, Clarke estimates that the average is about 68.4 tons per square mile for the land surface of the world, leaving out the polar areas which have little or no water drainage; or a total of 2,735,000,000 tons per year. Making certain corrections we may deduce from this that the land surface of the globe, which is subject to the solvent action of water, is lowered on the average by this agency one foot in 30,000 years.

Results of Solution on Carbonate Rocks. — Outside of the process of soil formation, in which solution also plays an important part, the most obvious results of its action are seen in the effects it has upon rocks wholly, or partly, composed of carbonates. The most important rock-forming carbonates are those of calcium, magnesium, and ferrous iron; $CaCO_3$, $MgCO_3$, and $FeCO_3$. Of these the first two, and especially the carbonate of lime, are the most important; vast stretches of the land being covered with beds of rock, hundreds or even thousands of feet thick, which are composed of them. Such rocks if they consist wholly, or mainly, of carbonate of lime are called limestone; if they contain much carbonate of magnesia, dolomite. In addition beds of sandstone, if they are not red or brown, may contain a cement of carbonate of lime holding together the grains of sand. Now since these carbonates, and especially lime carbonate, are attacked by water containing carbon dioxide in solution, as has been previously explained (page 24) with formation of soluble bicarbonates, it is obvious that under the action of atmospheric water, which always contains this gas to a greater or lesser extent, such rock masses as those mentioned must be continually dissolving and wasting away. This is shown in the fact that in those places where limestone, or calcareous sandstone, is the bed-rock the water is always *hard*, i.e. contains lime in solution, as proved by the deposit formed in tea-kettles. This work is most strikingly illustrated in the formation of sink-holes and caverns, which result from underground drainage.

Sink-holes and Caverns. — In regions where limestones form the bed-rock the surface waters working down joints and fissures may enlarge these by solution. Coming to an insoluble layer, such as one of clay or shale, they are stopped in their descent and spread

laterally, finding their way through the rock fissures along the natural drainage slope. These fissures are also enlarged by solution until they become distinct water channels. As the latter enlarge they form *caverns*, while the holes or pipes, leading down to them from the surface above, are termed *sink-holes*. The process is illustrated in Figs. 133 and 134.

Fig. 133. — Sink-hole in limestone beds; near Cambria, Wyo. N. H. Darton, U. S. Geol. Surv.

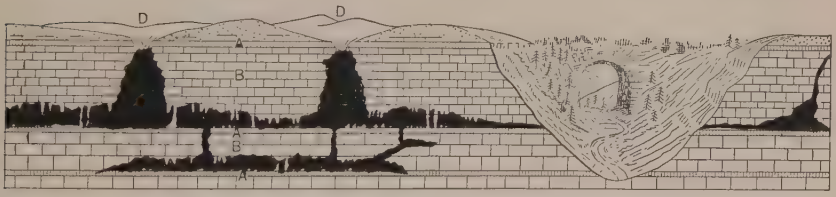


Fig. 134. — Diagram illustrating the formation of caverns and sink-holes in limestones. *A A* clay beds, *B B* limestones. The arch is the remnant of the roof of a former cave, forming a natural bridge. *D D* sinks, leading to domes below. Modified from Shaler.

The cavern domes hollowed out in the rock are sometimes 100 feet high or more and several hundred feet broad. They are connected by intricate passages. The floor on the insoluble stratum may be quite level for long distances. Breaking through this layer the waters may excavate new passages and chambers at a lower level, as illustrated in the diagram, Fig. 134, until there may be several sets of such rooms and galleries, one above the other.

The limestone regions of the middle West and South are noted for their caverns, some of the best known being Mammoth Cave in Kentucky, 10 miles

long or more, with 30 miles of winding passages; Wyandotte Cave in Indiana, Luray Cavern in Virginia, and many others. In some places the rocks are almost honeycombed with them.

It may happen in such regions that almost the entire drainage passes underground. Large rivers disappear from sight and, after a devious journey below, may come to the surface again in a different drainage area. In thus issuing they may give rise to huge springs, thus Silver Spring in Florida has an overflow so large that the resulting stream is navigable for small steamers, see Fig. 135. In other cases they may boil up as great springs in the sea, not far from land.

Fig. 135. — Silver Spring, Florida. G. I. Adams, U. S. Geol. Surv.

In addition to the caverns described above, limestones, where they are exposed to the weather, commonly show pitted, hollowed, or cavernous surfaces owing to the solvent activity of water. The same is true of calcareous sandstones, those with a cement of carbonate of lime; the latter dissolving, the sand grains fall apart and are washed or blown away. Many strange and often weirdly-shaped masses of rock are left as remnants through this combined chemical and mechanical erosion, see Fig. 132.

Deposition and Cementation. — From what has been previously stated it is clear that there is an upper belt in the earth's crust where mechanical and chemical changes and destruction are going on. It is known as the *zone of weathering* and extends downward to the level of the underground water. From this zone material is being constantly leached out and carried downward in solution into the ground water. This matter is either carried away by the drainage, or it may be deposited in pores, fissures, and cavities in the rocks. The lower limit to which this can extend is uncertain and appears to depend on several conditions and it probably varies in different

places. Thus the intervention of non-porous rock-layers, or the charging of the rock-pores with gas under pressure, would hinder, or perhaps prevent, further downward movement in a given area. In this belt whatever its thickness may be, the rocks are being solidified and cemented by the silica (quartz), carbonate of lime (calcite), and other substances deposited in them, and it is, therefore, known as the *zone of cementation.* A proper appreciation of this process and its results is of great importance, for by it we are able to understand the significance of certain geological features which will be considered later.

Deposits of Carbonate of Lime by Springs. — The material in solution which is not deposited in the rocks is carried away by the

Fig. 136. — One of the terrace formations of the Mammoth Hotsprings, Yellowstone Park.

drainage. Sometimes it happens that on its way to the sea it again comes to the surface and is temporarily deposited. This is best illustrated in the case of springs which deposit carbonate of lime. Many springs, and especially deep or fissure ones, contain carbon-dioxide gas, often in quantity and under considerable pressure, and thus when the water passes through beds of limestone on its upward way large quantities of lime carbonate are taken into solution, the amount depending on that of the gas under pressure. On arriving at the surface, partly through evaporation and partly by loss of gas through the relief of pressure, the lime carbonate is deposited, and in

this way mounds and formations may be built up which often display striking features and are of great beauty. They are illustrated in the basins and terraces of the Mammoth Hotsprings in the Yellowstone Park, Fig. 136.

In some springs, especially deep ones, the issuing water may be warm, or even hot. This is apt to be the case when they occur in regions of active or recently extinct volcanic activity, like that in which the Mammoth Hotsprings is situated. In warm waters the deposit of lime carbonate may be much increased by the action of low forms of vegetable life, *algæ*, living in them which secrete this substance from the water. It is probable that the warmth and chemical activity of the waters of some springs, particularly hot ones in volcanic regions, are greatly increased by gases and vapors coming from molten or heated rock masses lying in the depths below. As water vapor is believed to be the most considerable of these, the volume of water discharged may be increased by this agency.

In many cases the deposit takes place so rapidly that articles suspended in the spring become covered in a few days with a coating of carbonate of lime.

Other examples of such springs are found in Virginia, Colorado, Banff in Canada, Karlsbad in Bohemia, in Tuscany and in many other places. In addition to carbonate of lime, spring waters often contain other mineral substances in solution, sometimes entirely replacing it, and such mineral springs are often used medicinally, as at Saratoga and other health resorts.

Deposits in Caves. — The same process which forms caverns also tends to fill them up. For, after they have been made by underground drainage in the manner described above, the surface waters seeping down through the rock-beds which form their roofs dissolve more carbonate of lime and deposit it in them, producing stalactites and stalagmites, columns, pillars, etc. The manner of their formation is as follows. A drop of water, charged with lime leaking through to the roof hangs there for a time. While resting it evaporates somewhat and also loses some carbon dioxide and, consequently, deposits some lime carbonate. Finally, as it gathers volume, it drops and falling on the floor below it repeats the process, leaving another deposit. Thus there gradually grow downward from the roof long pendent incrustations, like icicles, which are called *stalactites*, while the rising deposits on the floor are known as *stalagmites*. Finally, these may increase so that they unite and produce columns. They are especially liable to form along lines of fissure in the roof. See Fig. 137.

In this way formations of great beauty and ones often exhibiting many strange and curious forms have been produced. In past times caves have served as refuges for primitive men who inhabited them, or as dens for wild animals. Through this the bones of men and animals, stone implements, and other objects have accumulated in them and been sealed up, like fossils, in the deposits of carbon-

ate of lime on their floors, to reveal to us, when broken open and explored, much concerning the life and degree of culture existing in prehistoric times.

Nature of Lime Deposits; Travertine, Tufa. — The character of the material formed when carbonate of lime is deposited from solution depends on circumstances and especially on the rate of de-

Fig. 137. — Stalactites, passing below into stalagmites, along a roof-crack. Marengo Cave, Indiana. G. P. Merrill, U. S. Nat. Mus.

position. When produced by slow evaporation, as in the stalactites in caves, it is a hard, compact, more or less crystalline substance. A general name for deposits of carbonate of lime from solution is *travertine*, from the old Roman name of a town (Tivoli) in Italy where an extensive formation of the substance exists. The so-called Mexican "onyx" or "onyx marble" is a travertine with banded structure brought out by varied tinting from metallic oxides. But when formed rapidly from springs, the travertine may be porous or loose, or coating vegetation it may be spongy or mosslike, and such less compact varieties are commonly called *calcareous tufa*, or sometimes *calcareous sinter*. Great deposits of this are also found around the shores of dried up alkaline lakes, such as Pyramid Lake in Nevada, encrusting the rocks of the enclosing basin, as mentioned on page 78.

It should be clearly borne in mind that these deposits are not *original* formations of carbonate of lime, in the sense in which we might think of that word in connection with limestone; they represent, certainly for much the greatest part, previously existent carbonate of lime, such as limestone, chalk, etc., which has gone into solution, been transferred to another place, and deposited. They merely exhibit a temporary stoppage of the material on its way to the sea, for it is the fate of all deposits of carbonates, exposed to atmospheric agencies, to be dissolved and taken into the ocean. Some have even had the view that thick formations of limestone, covering wide areas, have thus dwindled and disappeared, but this idea may be carried too far. What happens to the carbonates in the sea, and how the limestones, which furnish the secondary deposits of travertine and tufa, were made we shall see in a later place.

Other Deposits by Springs; Iron Oxides, Silica, etc. — Substances, other than travertine may be deposited when underground water issues at the surface. One of these is the hydrated oxide of iron, or under certain circumstances iron carbonate. This is a matter of importance because, as is commonly supposed, extensive beds of valuable ore have been thus formed. Also silica, sulphur, and gypsum may be deposited, but since agencies other than those which have thus far been described, are also, as a general thing, concerned in the process it is better to wait until these latter have been considered before discussing them.

Alkali Deposits. — In humid regions the soluble substances that are formed in the decay of the rocks are quickly washed out of the soil and passing into the drainage are carried into the sea. In arid and desert regions where the rainfall is scanty there may not be sufficient water to perform this function. The salts remain in the soil, at times of rainfall they go into solution and in the subsequent times of dryness, when the water draws to the surface, on its evaporation they are left forming the white incrustation on the soil known as *alkali*, a common feature in many parts of our western regions, see Fig. 138.

The common salts in the so-called alkali are sodium sulphate, sodium chloride, and sodium carbonate, Na_2SO_4, NaCl and Na_2CO_3; it is to the alkaline reaction and taste of the latter that the name is due. Magnesium sulphate, $MgSO_4$, and sulphate of lime, or gypsum, $CaSO_4 \cdot 2\,H_2O$ are also often present. These salts are not always formed by rock decay; they may have been originally present in the rocks if these are composed of beds of sediments laid down in the sea. Their concentration in such arid regions, with inland drainages, gives rise to salt and alkaline lakes. See page 78. The irrigation of alkali lands, especially

if the water is too freely or carelessly used, may bring the salts to the surface in such quantities as to injure, or even ruin them for agriculture.

Mechanical Work of Underground Water. Landslides. — As a mechanical agent underground water must play a small geological role. It is conceivable that streams running in subterranean channels may at times both erode and transport, but the circumstances which would permit this must be exceptional. A more important function is its aid in causing landslides, both in helping to overcome the friction of masses of rock, earth and débris lying on steep slopes

Fig. 138. — Alkali flat, Malheur Lake, Oregon. I. C. Russell, U. S. Geol. Surv.

and in adding weight to such masses. In producing such results it is often powerfully aided by the action of frost, as mentioned on page 20. The masses of earth and rock when saturated with water act like a semi-fluid substance and, started from their insecure foundations at times of extraordinarily heavy rainfall or by earthquake shock, rush down into the valleys below, often causing great damage and considerable changes of topography. In high mountainous regions such landslides, due to these causes and the shattered condition of the rock masses, may precipitate huge trains of broken rock, or talus heapings, for long distances downward, giving rise to rock streams. The onward motion of trains of talus, or "rock glaciers" as they have been sometimes called, due to freezing and thawing and gravitational creep has been already stated on page 109.

CHAPTER VII

ORGANIC LIFE AND ITS GEOLOGICAL WORK

Over the greater part of the land surfaces and in the sea, life, both animal and vegetable in varied forms, is present and, quickened by the energy imparted by heat and light from the sun, is causing movement of material on the earth's surface and transformations of matter by chemical changes. Compared with the vast bulk of the globe such actions, and their results, appear relatively superficial and small; from the human standpoint, however, they are not only great but of far-reaching importance and worthy of careful consideration.

Organisms work in various ways: in some cases they tend to break down existing structures and their action is thus *destructive*; in others they build new ones and their work is therefore *constructive*. Sometimes they preserve existent structures from the destroying action of other agencies and are thus *protective*. The most important protective effect is the influence of vegetation in restraining the erosion of the soil, a matter which has already been sufficiently treated (page 32) under erosion.

Destructive Work of Organisms

Destructive Work of Plant Life.—The most important geological process which plant life carries on in growing is to decompose the carbon dioxide gas in the atmosphere, storing up the carbon and returning to it the oxygen. This produces several important effects which will be considered in their proper places. On their death and decay the carbon of the vegetable tissues of the plants may be largely, or even wholly, reoxidized to carbon dioxide, and this being taken into solution by the descending surface waters forms carbonic acid, which, as we have already seen in several places, is a solvent of rock material.

The carbonaceous residue from the decay of vegetation existing in the soil which it colors dark, or black, is known as *humus*. In the production of humus not only carbonic acid but other compounds are formed, some of which are organic acids called humic,

ulmic, etc. These also attack the rocks and help to convert them into soil. Even the roots of growing plants secrete carbon dioxide and contain organic acids, such as citric acid, which exert a solvent influence on the minerals composing the rocks. Thus in its life, death, and decay vegetation is exerting a constant chemical effect upon the soil and rocks, changing the existing substances into new ones, many of which are soluble and carried away by the circulating waters. This is most strikingly seen in its effect upon the *oxides of iron* which color the soils red or yellow. They consist of *ferric* oxide, Fe_2O_3, usually more or less hydrated, as in limonite, $2\,Fe_2O_3 \cdot 3\,H_2O$, which makes yellow ocher when mixed with clay. Decay of organic substance is a process of oxidation; mostly the oxygen is taken from the air, but if the organic material is in contact with ferric oxide it will also take oxygen from it, reducing it to *ferrous oxide*, FeO. The ferrous oxide, however, as it forms, unites with the carbon dioxide, also being produced, and makes *ferrous carbonate*, $FeCO_3$. The process may be reduced to simple chemical equations by considering the organic substances, which really consist of carbon, hydrogen and oxygen, as if composed of pure carbon, as follows:

$$2\,Fe_2O_3 + C = 4\,FeO + CO_2, \text{ and } FeO + CO_2 = FeCO_3.$$

The ferrous carbonate, like calcium carbonate, is soluble in water containing carbon dioxide, and as this is always present to a greater or lesser extent, the iron compound is taken into solution, leached out and carried away. Thus while *ferric oxide*, so common a coloring material and cement in rocks and soils, is insoluble in meteoric waters, by the aid of organic matter it is converted into the soluble *ferrous carbonate*, dissolved and removed. What becomes of it we shall consider later.

Certain features regarding the coloring of rocks and soils are explained by this process. Thus the soil lying below a covering of vegetable mold (humus) is usually decolorized and, therefore, of light hue, or white, because the solutions of organic matter leaching downward from above have changed the iron oxide and removed it. This may be often observed on the sides of banks, railway cuttings, and excavations.

On the other hand, a clay which contains much organic matter is dark in color, dark-blue, dark-gray, or greenish to black. In such clay iron, if present, is in ferrous compounds on account of the reducing action of the organic substances and, as ferrous compounds have little or no coloring effect, the coloration is due to the dark carbonaceous material. When these clays are fired, however, the organic matter is burned out, the iron oxidized to the ferric condition, and red brick formed.

In desert or very arid regions the cliffs and rocks are usually strongly colored red, or less often yellow, because of the oxidation of the iron compounds in them

and the lack of vegetation in such places whose decay would reduce the ferric compounds and decolorize them. Thus vivid color tones are often characteristic of arid landscapes. The prevailing color of sandy deserts is, however, gray, often pale yellow, less often red.

With regard to the soils it may be said in general that while a red color is characteristic of many of the residual soils of today in warm moist climates, in ancient deposits, now hardened into rock, it is apt to be associated with salt and gypsum, which, as will be shown later, are indicative of arid conditions.

The importance of the principles here laid down will be seen later when the climates of past times in different places and their significance are treated and the formation of beds of iron-ore is discussed.

Fig. 139. — Rock split by a tree growing from a seed which lodged in a crack. Sierra Nevada, Cal. G. K. Gilbert, U. S. Geol. Surv.

In addition to the chemical work of plant life just described vegetation also acts in a *mechanical* way to destroy existent structures. The most important part of this work is seen in the splitting and disintegration of rocks by the roots of trees, shrubs and other plants. They insinuate themselves when minute into crevices and, expanding as they grow, they exert a disruptive force which even solid masses of rock are unable to withstand. Instances of this in exposed ledges and bowlders where seeds have lodged in cracks and have germinated and grown, enlarging the cracks and disrupting the rock, are

everywhere common. Such a case is illustrated in Fig. 139. In the course of long ages the amount of work done in this way, especially on rocks in the soil, must be very great, and the general action of weathering facilitated by the preliminary effect of roots.

Destructive Work of Animals. — Animals are much less destructive agents than plants yet on the whole they accomplish considerable geological work. It is done chiefly by those kinds which live and move about in the soil, such as worms, ants, moles, gophers, etc. By making holes, burrows, and upturning the soil they expose fresh surfaces to weathering and erosion, or by opening it up they facilitate the entrance of the weathering agents to lower levels. Thus Darwin states as the result of his investigations that in England the earthworms bring to the surface 10 tons of mold to the acre every year, while Branner believes that in many tropical regions the ants are even more effective in upturning the soil.

The most destructive animal in regions populated by him is Man, and this is due to the fact that over such wide areas he has felled the forests, and otherwise destroyed the natural vegetal covering of the soil, in order to cultivate it, thus throwing it open to attack by the agencies of erosion. This has already been discussed under erosion, page 33. The work of man as a geological agent is also seen in the diversion of drainages he has effected by wells, canals, dams, piers, dredgings, etc., although all of this is by no means destructive in its nature. The extermination of animals and plants, and the introduction of new species of both, in the settlement of new countries by man is also a process which has a geological bearing and has been going on at an increasing rate for an immense period of time, since Man first definitely assumed his position as master of living organisms.

There should be mentioned here also the chemical changes wrought by the decay of dead organisms in the sea, much of which is destructive in character. Both plants and animals contribute to these changes which take place chiefly on the bottom. The decomposing organic matter reduces the sulphates in sea water to sulphides with consequent formation of sulphuretted hydrogen, H_2S, which may precipitate sulphides, such as pyrite, FeS_2, or be oxidized to sulphuric acid, H_2SO_4. The acid may attack the lime carbonates in shells, and convert it into gypsum, $CaSO_4 \cdot 2\ H_2O$. This may serve as an example of chemical changes going on in the sea through the agencies of organic life. Carbonates, sulphates and phosphates are the chief results. *Diagenesis* is a general term for these processes which are of great importance in various ways as we shall see later when we shall have occasion to refer to them.

Constructive Work of Organisms

Constructive Work of Plants. — The manner in which plant-life acts as a constructive geological agent is best seen in the formation of peat and how by its production lakes are converted into bogs and swamps. This has been briefly mentioned in the life history of lakes, page 74, and may now be more fully considered. We will commence by learning what peat is and how it is formed.

Peat. — It has been previously stated that growing plants decompose the carbon dioxide of the atmosphere, using the carbon and largely returning to it the oxygen. In addition they demand water, which consists of oxygen and hydrogen, and certain mineral compounds furnished them by the soil. Their tissues, therefore, consist chiefly of carbon, hydrogen and oxygen, but contain mineral substances and in some cases also nitrogen in small amount. Disregarding the minor constituents, the chief substance composing their frame-work is *cellulose*, $C_6H_{10}O_5$, which for the sake of simplicity in this connection we may regard as forming the organic matter of plant life.

If dried organic matter, or cellulose, be burned with free access of air a complete process of oxidation takes place with formation of carbon dioxide and water vapor, as follows:

$$C_6H_{10}O_5 + 12\,O = 6\,CO_2 + 5\,H_2O.$$

If the heating, or burning, is conducted without access of air, or of but a limited amount, as when wood is charred in a kiln, or with earth thrown over it, the oxidation is incomplete, the hydrogen, oxygen and some of the carbon are removed, partly as above, but the greater part of the carbon remains as charcoal. Somewhat similar processes take place in nature when organic matter decays. Decay is caused by the growth and action of bacteria, minute organisms, and is a process of oxidation. If it takes place in the open air, as when leaves fall upon the ground, it may be in time complete and the cellulose returned to the atmosphere as carbon dioxide and water vapor, as if it had been burned.

On the other hand, if the organic matter decays where the access of air is prevented, as when plants grow in water or their leaves, twigs, stems, etc., in falling pass beneath its surface, a process somewhat analogous to the formation of charcoal takes place. The oxidation is only partial, some of the hydrogen being removed as water, H_2O, some of the carbon as carbon dioxide, CO_2, and some of both as marsh gas, CH_4. The resulting product of partly decayed organic matter is much richer in carbon and poorer in hydrogen than the

original material, and is known as peat. *Peat* is, therefore, the brown to black carbonaceous matter formed by the partial decay of vegetable matter in the presence of water.

The reason for the arrest of decay in this case appears to be that the bacterial life producing it evolves waste products, which, if not removed, are unfavorable to their continued growth and existence, that is, they are antiseptic in nature. When the condition is reached that the water saturating the decaying organic matter is changed to a sufficiently strong antiseptic solution from the presence of these substances, the bacteria can no longer exist, further decay is prevented and the peat formed is preserved.

Formation of Peat and Lake Filling; Bogs. — While peat is formed to some extent in warm and even tropical regions it is especially in temperate and cold humid countries that it is produced. Some of the various circumstances under which this happens and their results are discussed in the following paragraphs. Thus where lakes abound, especially in humid regions, a constant formation of

Fig. 140. — *A*, Bed-rock of lake basin. *B*, accumulating layer of peat; *C*, aquatic vegetation, pond-lilies, water weeds, etc.; *D*, bushes and semi-aquatic plants, mosses, etc.; *E*, climbing bog. (Modified from Shaler.)

peat in shallow water is going on, which is slowly but steadily filling them up. In the water are growing various kinds of aquatic vegetation, pond-lilies, water-weeds, rushes, etc. When these die their leaves, stems, and roots at the bottom form a black mud composed of peat. As these masses of vegetation, and the deposits they leave behind them, advance lakeward, bushes and semi-aquatic plants, such as certain mosses, appear in the shallowing water and close to the shore and add their quota to the peat deposits below. This is illustrated in the diagram, Fig. 140.

Eventually there comes a time when the peat formation reaches to the top, or nearly so, the basin is filled with the soft black mud which forms the final stage of the peat, the lake is obliterated and a *bog* formed in its place. See Fig. 141.

This process is especially important in small lakes and ponds, and in the shallow bays in large lakes where the depth is not too great for plant life to gain a foothold. In the larger and deeper lakes it may be at first a relatively unimportant factor in filling, compared with the deposits produced by incoming

sediments, but when the stage is reached where vegetation becomes abundant this may be reversed.

In northern regions the plants most efficient in forming peat are species of mosses, especially *sphagnum* (bog-moss) and certain flowering plants which grow rapidly, producing a spongy, cushion-like layer saturated with water. While growing above, the stems die below, making the peat. Where suitable conditions exist, especially in small lakes, the vegetation may push outward from the shore forming a floating mat. Eventually when the lake is filled by the de-

Fig. 141. — Lake filling; final stage where it is turned into a bog by accumulated peat. Near Hammond, La.

posited peat the bog-moss forms a cover concealing the black and treacherous quagmire below. Over wide regions, as in Newfoundland, Labrador, etc., not only the surface of filled lakes, or bogs, but all shallow depressions and in some places even the level ground, hill-slopes and hill-tops, even isolated rocks, are covered with this saturated layer, giving a bog-like aspect to the entire country. In sub-arctic regions, as in Alaska and Siberia, the country covered by this wet, mossy mantle of bog, which may be even continually frozen a small depth below, is known as *tundra*.

Southern Swamps. — In temperate to tropical regions the mossy bogs of the north are replaced by swamps filled with trees, bushes, canes, vines, etc., whose decay forms the peat. Such are the swamps along the lower Mississippi and its tributaries, the Great Dismal Swamp in Virginia and North Carolina and the marshes and swamps of Florida. Dismal Swamp covers an area 30 miles long by 10 broad, and appears to have been caused by the obstruction to drainage produced by accumulations of dense vegetation on a plain lying near sea-level. The trees covering it, of which the cypress is the most

characteristic of this and other southern swamps, maintain themselves in the soft peat mud by platforms of wide spreading roots. In the swamp is Lake Drummond six miles in diameter but very shallow, its banks and bottom composed of pure peat. A view in this swamp is seen in Fig. 142. In tropical regions, as in the basins

Fig. 142. — Dismal Swamp, Va. The projections from the cypress roots serve to give them air; they extend downward into the mud and help to anchor the tree in the semi-liquid mass of the bog. I. C. Russell, U. S. Geol. Surv.

of the Amazon and Nile rivers, vast swamps and marshes occur, formed by the obstruction to drainage caused by the rapid growth and accumulation of vegetation on an enormous scale, especially of aquatic kinds, such as rushes, canes, etc. These also give rise to peat deposits.

Marine Marshes. — In bays and harbors along sea-coasts and on the deltas of large rivers vegetation plays a prominent part in helping to turn shallow water areas into marine marshes. For when the depth of water is sufficiently small, or becomes so through deposit of sediment, marine vegetation, partly growing completely submerged, or aquatic, like eel-grass, partly semi-aquatic, like certain grasses and rushes, takes root and flourishes. At high tide this band of vegetation may be well covered with water, but, as the tide recedes and its current slackens, sediment and floating matter borne

by it are entangled among the stems in the fields of grass, and sink to the bottom. The stems, leaves and roots of the grasses, along with seaweeds, on decaying make peaty material. The mingled deposit of sediment and organic matter thus rises until it reaches high tide level, new kinds of fresh-water plants coming in to replace the plants first mentioned, which move seaward as the water shallows, and thus marine marshes are formed, often overlaid by fresh-water plants. The process is illustrated in Fig. 143, and is often the final stage of filling of the sounds and lagoons formed by wave action, page 99.

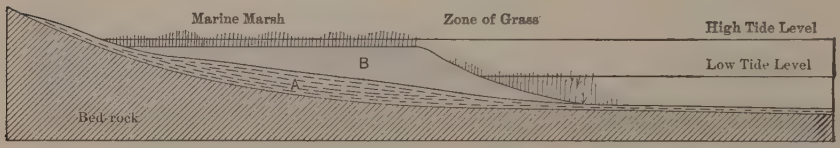


Fig. 143. — Illustrating the formation of a marine marsh. *A*, sedimentary deposits; *B*, peaty mud deposit formed by action of vegetation. Modified from G. P. Merrill.

In the low marshy regions about the deltas of great rivers such as the Mississippi, which are sometimes inundated by the sea and sometimes covered by fresh-water from the river in times of flood, similar processes prevail, although over wide stretches pure peat may be the only deposit laid down, since the vegetation may be so dense as to cause the water to quickly deposit all its sediment before reaching the interior of the swamp or marsh.

On the shores of warm seas, as on the coast of Florida, mangroves, which are small, many rooted trees growing only in sea-water, perform a somewhat analogous function in making marshes. Their maze of roots entangle sediment and other matter, and help to form a barrier to the escape of water from the land. By this means shallow stretches of sea-bottom have been changed into swamps and marshes, as in parts of the Everglades.

Properties and Uses of Peat. — Peat varies from a brown, spongy, fibrous, or matted mass, resembling tobacco when least altered, to a fine, black, granular mud, when most changed. The latter, when dried and compressed, much resembles lignite, or brown coal. Peat, when cut and dried in the form of turfs is much used in many countries, especially in Europe, as a cheap fuel; in North America, owing to the abundance of wood and coal, it has, up to the present time, received little attention. The amount of it in the United States in the various bog and swamp areas is, however, enormous, being estimated by the Geological Survey at 12 billion tons of air-dried fuel; with the increasing scarcity of wood and upward tendency in the price of coal, and the discovery of its value as a source of power in

the gas-producer engine, it will probably have a growing use in the future.

The antiseptic quality of peat bogs has been already mentioned; this is strikingly shown in the preservation of the bodies of men and animals which became entombed in them many hundreds or even thousands of years ago. Trunks of trees and their stumps have also been preserved, and in some places cedar logs thus buried have been extracted and used for the valuable timber they afford.

Relation of Peat to Coal. — The principles which have been laid down concerning the origin and formation of peat are of the greatest importance regarding a correct understanding of the origin of coal and the conditions under which it was formed. Peat is the first stage in the transformation of vegetable matter into coal. Further stages and the kinds of coal will be considered in a later place. It is important to observe, however, that in certain places where subsidence of the earth's crust and deposit of sediments are going on, as in the deltas of rivers such as the Mississippi and the Ganges, borings show that layers of peat, often of considerable thickness, are found alternating with beds of sands and clays, just as layers of coal are found between beds of shale and sandstone.

Reclamation of Swamp-Lands. — It is estimated that over 100,000 square miles of the United States consist of swamps, bog, or inundated land, which in its present condition, although valuable in places for the timber it contains, is useless for agriculture. By the use of suitably placed canals and ditches, a very large, perhaps the greater, part of this land can be drained and rendered available for cultivation. It generally possesses a very fertile soil. Some work has been done towards reclaiming these swamp and marsh lands, as in Florida, California, and in the Dismal Swamp, with results like those shown in Fig. 144. With the closer settlement of the country and consequent greater demand for land, and with the initiation of reclamation projects in these inundated areas by the National Government, we may expect to see in the future a constantly increasing use of swamp lands.

Diatom Deposits. — It has been already mentioned (page 107) that siliceous deposits, which occur over vast stretches of the sea floor, are composed of the shells of diatoms, extremely minute uni-celled vegetable organisms. These also live in lakes and marshes and even in warm springs and pools, as in the Yellowstone Park, and living and dying in almost unimaginable numbers their shells form deposits, often of considerable thickness. This white, porous, chalk-like deposit of silica, SiO_2, is known as diatomaceous earth, or *tripolite*, and beds of it several hundred feet thick have been found in places. It is used for several purposes, such as polishing powder, in making dynamite, etc.

Iron-ore Deposits. — In a previous section we have shown how, by the influence of organic matter, iron in the rocks and soils is reduced from ferric to ferrous oxide and taken into solution. It now becomes pertinent to inquire what becomes of the iron. When thus brought into solution it is leached out and in standing bodies of

Fig. 144. — Reclaimed land from the Dismal Swamp, Va. I. C. Russell, U. S. Geol. Surv.

shallow water, such as swamps, lagoons, or estuaries with small outlets to the sea, it may be concentrated and give rise to considerable deposits. The beds of Clinton iron-ore, extending from western New York southward to Alabama, are examples of these. Under some conditions these beds may be of ferrous carbonate (siderite, $FeCO_3$) directly, but usually the solution of the carbonate is reoxidized, carbon dioxide escapes, and the iron is precipitated as ferric hydroxide, limonite, as follows:

$$4\,FeCO_3 + O_2 + 3\,H_2O = 2\,Fe_2O_3 \cdot 3\,H_2O + 4\,CO_2.$$

The most interesting feature of the process is that the oxidation from the ferrous to the ferric condition is largely performed by certain exceedingly minute vegetable organisms living in the water, which are known as the iron bacteria. These secrete the iron from solution and change it in their cells from the ferrous to the ferric condition, thus rendering it insoluble. Although so excessively minute, yet occurring in such enormous numbers, they may give rise to large deposits.

The ferric hydroxide thus precipitated may accumulate on the bottom as *bog iron-ore*, or limonite, or, as in swamps, it may again come in contact with decaying organic matter and be changed back into ferrous carbonate. Such beds of ore may be quite pure, or, mingled with clay or sand, they may form deposits of impure limonite, clay-ironstone ($FeCO_3$), etc. This may also explain the fre-

quent occurrence of beds of iron-ore and of coal (ancient peat bed) in the same series of stratified rocks, and why, in this case, the ore is so often ferrous carbonate. Some are inclined to believe that all beds of iron-ore found in the stratified rocks are due to these processes, and, therefore, always indicative of the former presence of vegetable life, but this is going too far, for iron-ores may be concentrated in other ways. But, in general, it may be said that such beds are presumptive of the former existence of organic life.

Constructive Work of Animal Life. — The geologically constructive work which animal life performs has its results chiefly in the deposits which they leave behind them. By far the greater part of these deposits is composed of carbonate of lime, a small and much less important part of phosphate of lime. The deposit of carbonate of lime through animal life takes place now, and has taken place in the past, on an enormous scale and is a geological process of very great importance; it occurs chiefly in the sea and is most strikingly illustrated in the work done by corals. One phase of it has already been alluded to in speaking of deposits on the sea floor, page 106.

Coral Reefs and Islands

Corals. — These are small animals of a low order of life. The individuals are called polyps, are simple in organization, consisting chiefly of a soft sac-like body containing a stomach, a mouth, and a fringe of arms, or tentacles, around it, with which they capture their food. Further details respecting them may be found in Chapter 35. One function of the animal is to extract carbonate of lime from the sea-water, and, depositing it in the lower external part of the body, to build up a stony base upon which the animal lives and flourishes. Living together in colonies, as do most of the reef-corals, this stony base grows and assumes the varied shapes seen in masses of coral, such as branching forms, plates grouped in aggregates, half spheres, etc. See Fig. 145. Coral trees or the "staghorn" corals may be 15 feet high and the half spherical head corals 15 feet across. Such growths support an enormous number of individual polyps. While there are many kinds of corals, the most important geologically are the reef-building ones. These are not found everywhere in the ocean, but only where certain suitable conditions prevail. The conditions demanded are as follows: *a*, the water must not have a mean temperature lower than 68° F.; *b*, the water must be clear and salt, free from the products of land waste; *c*, the water must be shallow, not over 240 and preferably less than 150 feet in depth. An abun-

dance of food is also necessary, and the great westward tropical ocean currents, described on page 84, seem to carry this and produce very favorable conditions for corals as they flow against the eastern continental shores. Thus the eastern shores of Africa, Australia, and Central America support extensive coral formations, while on the western shores of these continents they are comparatively rare.

Fig. 145. — View of corals on a reef at low water. Great Barrier Reef, Australia, Savile Kent.

Coral Reefs. — Corals grow upward and spread laterally and the stony base continually increases, branching out; or the coral heads enlarge. As they die the lime carbonate base is left and, mingled with the shells of various kinds of shell-fish, the tubes of worms, and the bones of marine animals inhabiting the coral thickets, and with branches and pieces of coral broken from the living forms above, forms a constantly accumulating layer. The warm sea-water cements the coral fragments together and eventually converts the deposit into a white solid limestone upon whose upper surface the living corals grow and flourish. This forms the *coral reef*. It rises until its surface is just below the level of low tide, only occasionally laid bare at the lowest tides for short periods, for corals can stand exposure to the air only a limited time. Over it the waves boil and break and at its outer edges the reef-building corals thrive best, for in the rush and dash of the waves they find the most food and lime in the water and here the latter is clearer, more aerated and thus furnishes more of the needed oxygen.

In addition to the corals all such reefs have many other forms of animal life living on them and some of these, such as hydroids, also contribute by lime deposits to the up-building of the reef. Even plants (nullipores, etc.) add their share by secreting lime from the sea-water, and it seems probable from recent investigations that they have been a much more important factor in helping to build the reefs by this accumulation of material than had been previously supposed.

Coral Islands. — The term coral island has been used in several ways and unless strictly defined is liable to misinterpretation. There are a great number of islands in the tropical oceans, especially in the Pacific, which for the most part are of volcanic origin, like Hawaii for example; a few are high islands composed of rocks which are not volcanic, or only partly so, like Fiji and New Caledonia. These are more or less surrounded by coral reefs, in ways which will pres-

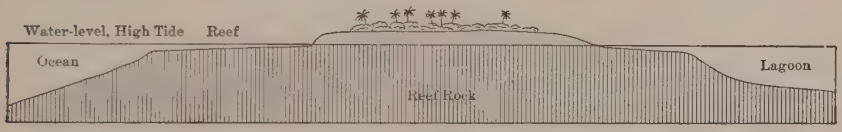


Fig. 146. — Section through coral reef and island upon it. (After Dana.)

ently be described, but they are evidently not *coral* islands. They are oceanic islands with coral reefs. See page 107. But, by the action of the waves masses of coral, often large coral-heads, and blocks of reef-rock are broken off and thrown up on the reef, other fragments and coral sand fill in between them and finally by the beating of the waves the whole mass, resting on the broad platform of the slightly submerged reef, is compacted and rising above water becomes an island. These are true *coral islands* and the mode of their formation is similar to that of barrier islands. See page 98.

The islands thus made are low, usually not more than 15 feet above sea-level, and from a quarter to half a mile wide, though often long in the direction of the reef. They are usually covered with vegetation, are of great beauty, and sometimes inhabited, though their lowness subjects them to the danger of being swept by the sea in times of heaviest storms. A section of a reef with a coral island upon it is shown in Fig. 146.

Classes of Coral Reefs. — According to their position and arrangement coral reefs have been divided into three general classes which are known as *fringing reefs*, *barrier reefs*, and *atolls*. The characters which distinguish them are as follows:

Fringing Reefs. — In the shallow water around any existing land where the conditions are right corals grow and gradually build up a platform to sea-level, forming a bench extending outward from the land edge toward the sea, as shown in Fig. 147. The width of the reef seems to depend on the steepness of the land slope; if this is great the reef is narrow, if gradual it may be several miles wide. Opposite streams coming from the land the reef is wanting, since these produce unfavorable conditions of fresher and muddy water.

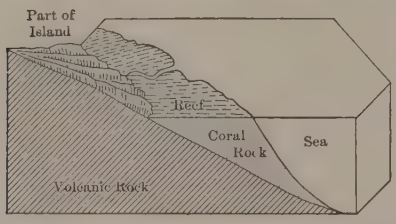


Fig. 147. — Section through land, and attached, fringing reef.

For reasons already explained the corals chiefly grow and flourish on the outer edge of the reef. The seaward slope of the latter is very steep. As material is broken off by the waves and rolls down this slope it gradually becomes compacted by deposit of lime carbonate and forms a rising talus upon which eventually the corals grow and advance the reef sea-ward.

Barrier Reefs. — This kind of reef differs from the fringing one in that it is situated some distance from the land with a stretch of shallow water between, forming a lagoon or channel. Many of the high volcanic islands of the Pacific are more or less completely girdled by such an encircling reef. See Fig. 148.

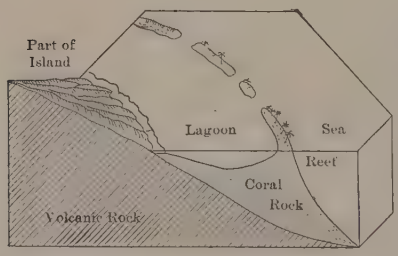


Fig. 148. — Section through land and distant barrier reef with lagoon-channel between.

Openings or breaks exist in these reefs sufficiently deep to permit the access of vessels to the lagoon-channels, which thus serve as harbors; the channels, which have an average maximum depth of 200 feet, are, however, often too shallow for navigation. The barrier may be from one to thirty miles from the land; often they support islets upon them which may be wooded. The west coast of the island of New Caledonia has a reef of this character that extends for 400 miles, while the greatest of all is the great barrier reef of Australia which stretches for 1200 miles along its eastern side with an average distance of 20–30 miles from the mainland, and with a depth of 100–300 feet in the channel. A view of a portion of this reef at very low water, with the living corals growing on it, is seen in Fig. 145.

Atolls. — These, like many barriers, are more or less imperfectly ring-shaped reefs, but without any island within, only a lagoon of comparatively shallow water, as indicated in Fig. 149. The breadth of the ring may be from 2 to 50 miles; generally there are openings, usually on the leeward side, affording access to the lagoon. The depth of water in the latter may be from a few feet up to 300, but averages about 200; on the outside the reef may descend quite sharply thousands of feet toward the ocean floor. Like the other reefs mentioned they may support wooded and inhabited islands upon them. A view of an atoll is seen in Fig. 150. Such atolls are one of the most striking features of the Pacific ocean.

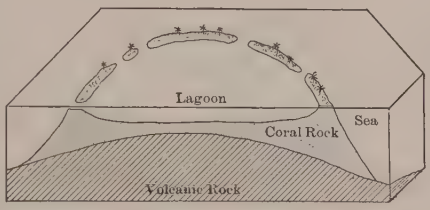


Fig. 149. — Section and plan of an atoll.

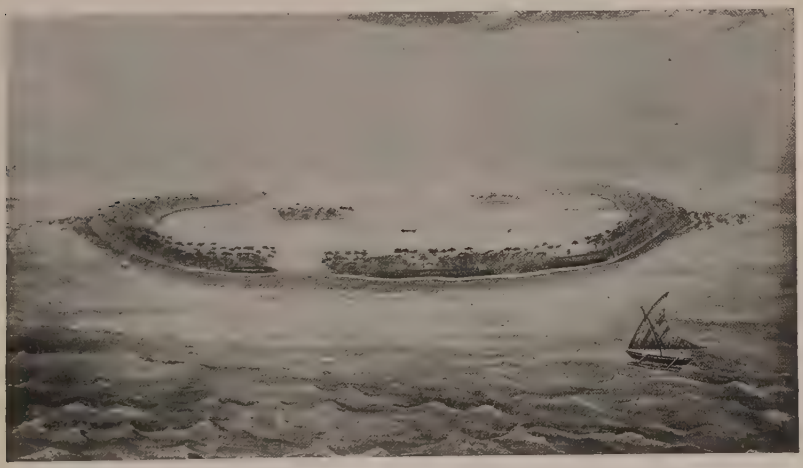


Fig. 150. — View of an atoll; after Dana, from an old picture.

Origin of Barrier Reefs and Atolls. — Fringing reefs require no special explanation; their origin is simple and may be understood from the description of them. But barriers and atolls are difficult to understand, both from their form and from the fact that they appear to rise from the bottom of the deep ocean, thousands of feet below the limit at which corals can grow. How then did these curious structures originate? In the attempts to answer this question processes have been invoked which make the explanations im-

portant from the bearing they have upon geological problems of great significance.

Subsidence Theory of Darwin and Dana. — An explanation which for a long time received general acceptance was one offered by Darwin and elaborated by Dana. According to this hypothesis the three kinds of reefs represented successive stages in a continuous process produced by gradual *subsidence* of the ocean bottom. The idea involved may be easily understood from inspection of the diagram, Fig. 151. Around some island, produced perhaps by

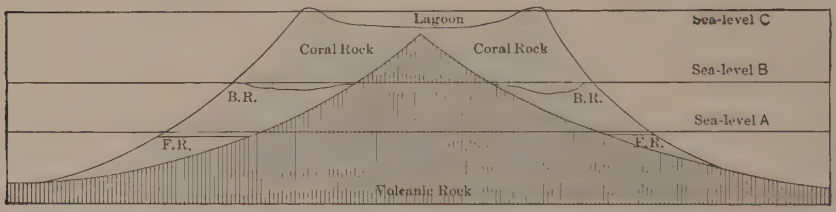


Fig. 151. — Section showing the formation of barrier reefs *BR* and an atoll from fringing reefs, *FR*, by gradual subsidence; sea-level remaining permanent but assuming relations *A*, *B* and *C*.

volcanic agencies, corals attach themselves and grow, forming a fringing reef *FR*. The sea level is supposed to be at *A*. As the island gradually sinks, the sea-level remaining the same, it assumes with respect to the land the position of *B*. Meanwhile the corals keep building the reef upward and for reasons already given most rapidly on the outer edge and thus the fringing reef becomes the barrier *BR*. By a continuation of the process the island disappears and the barrier becomes an atoll, as in *C*. It is understood that the rate of submergence is not greater than the upward growth of the coral reef. There are facts which seem to confirm this theory but as a sufficient explanation for all kinds of coral islands, objections have been urged against it.

What seems to confirm it are the facts that all gradations between the three kinds of reefs may be found and that there are positive evidences of recent submergence in some cases, such as the dredging of dead and drowned corals from the reefs at depths below the limit of coral growth; stone houses of natives once built on the shore and now surrounded by water, etc. A boring in a typical atoll went down over 1000 feet in lime carbonate rock, indicating corresponding subsidence and up-building. The topography of the coast-line of the volcanic islands with barrier reefs also shows subsidence, since there are no sea-cliffs cut into them, the streams have no deltas, but drowned river mouths, and the shore lines are very irregular.

The objections to this view are that it requires a general subsidence of thousands of feet of the earth's crust over such a vast region, some 20,000,000 square miles of the sea floor of the Pacific, as well as subsidence in other oceans. It has been also pointed out that in some island groups there are atolls in one place and raised coral reefs in other ones not many miles distant. Where reefs have been raised they are found not to be over 250 feet thick.

Theory of Murray and Alexander Agassiz. — This attempts to account for barriers and atolls without subsidence. We imagine first a platform to be raised in some way from the ocean floor up to the required depth for coral growth. This might happen by volcanic eruptions and up-building; sometimes the volcanic masses would protrude from the sea and form islands; sometimes they would be not very high above sea-level and would be cut away by the waves to shallow water platforms, and sometimes when not up to the required level they might be raised to it by lime deposits from the shells of marine organisms. Or, as Agassiz suggests, the platform might be made by the latter method alone. Around such islands and on the platforms thus made coral would grow and, thriving best on the outer edges of the reef, the latter would expand and move seaward, advancing on the talus forming at its front. In the meantime the dead portion of the reef left behind, bored into by innumerable organisms, would crumble and, partly by the solvent action of the sea-water and its supposed contained carbon dioxide, and partly by the scouring of currents, would be gradually removed and in its place would appear the channels and lagoons. Thus where there was an original island the fringing reef would move away and become a barrier; where only a submarine platform was present it would move to its outer edges and form an atoll.

The chief objection to this view is the great size and depth of many lagoons and channels; 30 miles wide and 200 feet deep; it seems improbable, if not impossible that such enormous masses could be removed in this way. Moreover the study of atolls shows that the lagoons tend to fill up rather than to deepen, that lime carbonate is depositing in them rather than being removed by solution. It also does not account for the general evidences of recent submergence mentioned.

Rise of the Water-level. — Quite recently Professor Daly has urged the importance of a rise in the water-level of the oceans as an explanation for the origin of barriers and atolls. The cause of this increase of water in the oceans is attributed to the gradual melting of the vast continental ice-caps which covered in a recent geological period the North and South Polar regions, and extended down into what are now temperate latitudes, as will be described more fully in a later place. They covered millions of square miles and were several thousand feet in thickness. The gradual accumulation of this ice lowered the water-

level in equatorial regions, and its gravitative effect, in drawing the oceanic water toward it, tended to lower the level still more. Daly calculates that these effects lowered the level of tropical seas from 200–250 feet. Owing to the colder condition of the earth, and thus of the seas, it is inferred that coral life was restricted to very narrow tropical belts. Elsewhere the islands, undefended by caps and belts of growing coral, were exposed to the erosive action of the waves, which cut wide terraces around the harder and larger ones, while small ones, and those of softer, less compact material were cut off, forming platforms at sea-level. When the ice melted and the seas grew warmer the corals are supposed to have returned to these islands; on the terraces around the former, growing best at the outer edge, they formed barrier-reefs, while of the submerged platforms they made atolls. Since the reefs grew upward, as the water gradually deepened from the melting of the ice, the interior lagoons and channels were formed, and these since then have been gradually filling up. This is taken to account for the general depth of 250 feet of the platforms below sea-level, for the usual depth of about 200 feet in the larger channels and lagoons, and for the evidences of apparent subsidence previously mentioned.

The correctness and value of this view as an explanation of the varied features of coral islands and formations mentioned, and its general bearing on geology can only be ascertained by a careful comparative study of varied groups of islands, especially of their topography, and of the relations of coral formations of past ages. It also depends on the amount of water withdrawn from the sea, and turned into ice, and the data on which this in turn depends are at present too vague to enable us to calculate this with any precision. The amount of landward cutting by wave action at the lowest stage of water-level, in view of the time demanded, would in some cases seem excessive. It is in one respect a reversal of the Darwin-Dana view, but, like that, demands a change of water-level.

General Explanation. — From what has been said in the foregoing pages it appears that widely divergent views have been, and still are, held regarding the origin of the peculiar features seen in barrier reefs and atolls. Our knowledge in several directions does not seem sufficiently extensive to afford a general explanation which would be universally accepted at the present time. It should be pointed out that the views of Darwin and Murray are not necessarily exclusive of each other. Barriers and atolls could be formed on either assumption, if other conditions were right, and outward spreading growth and submergence might be occurring simultaneously. If subsidence were the only factor we should expect a great thickness of coral rock in atolls, whereas borings in one in the Pacific, and quite recently in Bermuda, show only a relatively thin capping of it on the volcanic rock which forms the main masses rising from the ocean depths. Quite recently Vaughan has called attention to the fact that there are shallow water platforms in warm seas which, in places, are devoid of coral formations of barriers and atolls, like the one surrounding eastern Australia, which shows that the platforms

antedate the settlement upon them of the corals, and are, therefore, independent of them. He also shows that the crescent or ring shape of atolls may be due to the effect of prevailing winds and currents; the apex of the crescent pointing toward the direction of current arrival. Further, recent chemical investigations show that the water in the lagoons has no solvent action but is really precipitating lime which tends to fill them up. The suggestion urged by Daly may prove of value as one factor in helping us to understand the generally uniform depth of water on the shelves which support barriers, and in the lagoons of atolls, and those features which appear obviously due to changes of water-level without having recourse to vast subsidences of the floors of entire oceans, as needed by the Darwin-Dana theory. It should be noted, however, that other factors may produce changes of water level. Thus, over the vast extent of the ocean bottom, which covers three-quarters of the globe, relatively slight warping movements here and there through long periods of time, causing upward and downward movements over local areas, would register themselves by changes of water-level on the shores. It seems probable that the formation of the coral-island structures is a complex one, due to a combination of several agencies, which operated with varying intensities in different places, and that we cannot advance one single factor which will cover all cases, and afford a general explanation.

Lime Carbonate Deposits; Limestone. — A great variety of animals living in the sea are constantly extracting from it carbonate of lime for their own uses. In the sea-water it exists as the soluble bicarbonate, $H_2Ca(CO_3)_2$, the animals convert it into normal carbonate, $CaCO_3$, the insoluble form, and for each molecule thus converted one of carbon dioxide, CO_2, is set free. This they do to produce hard parts which shall support or protect their soft parts. Familiar examples are the shells of mollusks, such as clams, oysters, sea-snails, conchs, etc., or the supporting structures of corals. There are also many kinds of minute free-swimming animals of low, or very simple, types of organization living in the upper layers of sea-water which have protective calcareous shells. One important group of these is known as *foraminifera*, examples of whose shells are seen in Fig. 89. Generally they are not larger than a grain of sand. It has been found that the lime deposits in the sea are also largely due to the action of small forms of vegetable life, varieties of *algæ*, floating in the upper layers of the water, which secrete lime from it. See also page 104.

These varied kinds of life, small though they may be in the indi-

vidual, through their enormous numbers and working through long intervals of time, have produced by their shells and other structures deposits of carbonate of lime, which in places are of vast extent. These deposits, accumulated on the sea-floor, according to their degree of compactness and other characters, as we are able to determine them after they have been raised and turned into land surfaces, are known as *chalk* and *limestone*. Limestone, therefore, is a sedimentary deposit of carbonate of lime made by organic life in the sea.

This work is, perhaps, most conspicuously seen in the formation of the coral reefs previously described. A coral reef might be likened to a factory for the manufacture of limestone. Along with the corals a variety of other organisms are busily at work, shellfish of different kinds, some of which bore into the coral rock and help to crumble it; worms (*Serpulæ*) which form calcareous tubes and whose colonies may form miniature atolls, as at Bermuda, Fig. 152, and even

Fig. 152. — Serpuline atoll. Bermuda Island. These structures formed in shallow water may be a number of feet, or yards, in diameter and are locally called "boilers."

some types of sea-weed (nullipores) which secrete carbonate of lime and produce coralline structures, while foraminifera swarm in the waters and add their quota of shells to the deposits. Nor is the deposit confined to the reefs and their immediate neighborhood. The coral rock, broken by the waves and ground up to fine sediment, is distributed over the sea floor, the water being muddy with it after heavy storms for miles away from the reef. Such fine substance consolidated by pressure of overlying material, and by solution and re-deposition, forms compact limestone. The rock is often dense and structureless, and without fossil remains through great thicknesses, in other cases filled with corals, shells, etc. As beds of limestone are found piled up in thicknesses of hundreds and even thousands of feet it must be inferred that their formation has required enormous periods of time. Agassiz has estimated that it would take about 1000 years for a coral reef to grow upward 40 feet. It is especially in the warm waters of tropical and sub-tropical seas that the conditions are suitable for those forms of life which deposit carbonate of lime, and where it therefore accumulates

in greatest amount. Therefore, the presence of thick beds of limestone is held to indicate warm climate as prevailing in that region at the time of their formation.

Shell Limestones; Coquina. — There are many varieties of limestone depending on the mode of formation. Thus in some there are abundant remains of some particular organism which contributed most largely to the deposit in the form of fossils and which thus give the rock a particular character. It may be composed almost entirely of shells with fine carbonate of lime between them acting as a cement. Such rocks are sometimes called 'shell limestones.' A light fragile rock consisting of shells and their fragments somewhat compressed and cemented, now forming on the coasts of Florida, is known as *Coquina*, from the Spanish word for shell.

Chalk. — This well-known soft, slightly coherent rock consists of a fine calcareous powder which the microscope shows to be largely composed of the tiny shells of foraminifera and microscopic plants (*algæ*) mingled with fragments of other shells, etc. It commonly contains hard nodules of siliceous material called flint, which are supposed to represent the concentrated hard parts of certain organisms which secrete silica.

It has been customary to consider chalk a formation produced on the bottom of the deep sea, from its resemblance to the calcareous oozes, or muds, found at the bottom of modern oceans. See page 106. It would seem, however, not to have been formed as a deep sea deposit since it always contains fossils indicative of shallow water, as well as skeletons of birds, pterosaurs (flying reptiles), etc. The facts in most cases would point to its having been formed in clear, shallow and warm sea-water, free from products of land erosion.

Dolomite. — Although limestones when first formed consist of lime carbonate, $CaCO_3$, in process of time they have been in places more or less completely converted into dolomite, $CaMg(CO_3)_2$. Even if not pure dolomite, if they contain any considerable quantity of magnesia, they are still often referred to as dolomite, or dolomite-limestone. While this change probably takes place in greatest amount in the sea, whose waters contain magnesium salts in solution, see page 83, and especially where the water is warm and shallow, it apparently may occur on land also, caused by several agencies, the upward movement of warm waters containing magnesium salts for example, but is much more restricted in extent. Dolomite is a more stable compound than calcium carbonate and forms a denser, more insoluble rock.

Phosphate Deposits. — These, while not making geological formations of great extent and importance, are of interest and of great commercial value from their use as fertilizers for the soil. When found in sedimentary beds we ascribe their origin chiefly to the calcium phosphate of the shells of some marine invertebrate animals (brachiopods, heteropods, etc.), and the bones and excrement of vertebrate animals, concentrated often by being leached down and re-deposited. Thus they occur in Tennessee, Florida, the Carolinas,

and other parts of the South. A modern illustration of their formation is seen in the deposits of guano, the excrement of sea-birds in certain places in arid regions, as on the west coast of South America. The calcium phosphate it contains comes chiefly from the bones of the fishes which form their food.

CHAPTER VIII

IGNEOUS AGENCIES; VOLCANOES

The various agencies which we have so far considered as modifying the surface of the earth, such as the atmosphere, water in its forms of rivers, seas and ice, and plant and animal life, derive the energy which enables them to move and perform their work from a source exterior to the earth; from the sun. For, without the sun, these movements would cease and the earth's surface would be dead and inert. Toward these agents the earth is passive, except as it adds the force of gravity to help them in their work. An exception to this principle may be found in the chemical work of underground water, otherwise it appears to be a general one.

We have now to consider a set of agencies which are also modifying the earth's surface, whose energy on the other hand is derived from sources within the earth itself. So far as we can judge they appear to be due, either directly to the interior heat of the earth, or to changes going on within which produce heat. We shall describe first the results as seen at the surface and then inquire into the possible origin of them.

When we regard the changes going on within and the concomitant heat as geological factors, the processes and results which they give rise to at the surface may be grouped as follows:

a. Volcanoes and igneous phenomena.
b. Hot springs and fumeroles.
c. Changes in position of the earth's crust.
d. Earthquakes as a result of *c*.

Volcanoes

General Description. — Volcanoes are elevations composed of materials collected around a vent from which they have issued from the earth's interior in a highly heated or molten condition. In its typical aspect a volcano is conceived of as a steep conical mountain with a pit-like crater at the top from which issue from time to time gases, ashes, bombs, and flows of molten rock called *lava*. The ejection of material is termed an *eruption*, and volcanic eruptions are to the human mind, perhaps, the most impressive of geological

phenomena, from the immensity of the forces displayed, the magnitude of the results achieved, and from the disastrous consequences which they frequently entail. Volcanoes vary widely from the typical form mentioned; they may be low and flattened, or high and steep; conical, or elongated and irregular in shape, while the crater may be at the top, or on the side, of variable shape, or even wanting.

In size volcanoes may vary from small cones one or two hundred feet high to those which form some of the loftiest mountains on the globe. Thus some of the highest peaks of the Andes are formed by volcanoes, some of which are still active, as Cotopaxi in Ecuador, 19,600 feet high with a crater half a mile in diameter and 1500 feet deep, while others like Aconcagua, 23,000 feet and Tupungato, 21,500 feet, on the border between Chile and Argentina, and Chimborazo (20,500), in Ecuador, which apparently have no craters and are

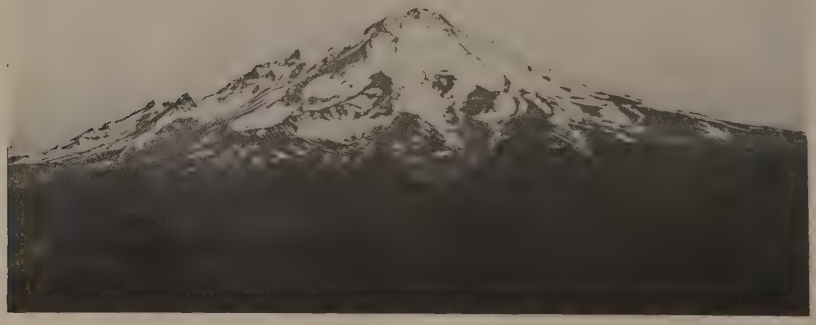


Fig. 153. — Mt. Shasta, Cal. J. S. Diller, U. S. Geol. Surv.

not now in activity, have geologically only recently become extinct. These are built, however, upon a dissected uplift, or platform, of much older rocks above which they rise 10,000–12,000 feet, but in the case of the Hawaiian Islands the volcanic piles are placed on the sea-floor, some 14,000–18,000 feet below the surface, above which the highest summits project about 14,000 feet, thus making the whole mass some 30,000 feet in extreme height. In the United States the higher peaks of the Cascade Range, beginning with Mt. Shasta (14,400 feet), Fig. 153, in northern California and including in Oregon and Washington Mt. Hood (11,300), Mt. Adams (12,470), Mt. Rainier (Tacoma), (14,500), and Mt. Baker (10,800) are volcanoes, which are now quiescent, or have recently become extinct. Mt. Etna, on the coast of Sicily rises about 11,000 feet above

sea-level and the diameter of the base of the conical pile is about 30 miles. The lower slopes are gentle and studded with many small, minor, or parasitic, cones.

Character of Eruptions. — At volcanic vents three things may be ejected, gases, liquids consisting of molten rock, and solid material in the form of fragments, and the nature of a volcanic eruption depends largely on the proportions and relations of these three things. If the eruption is violent and explosive in character then the gases have been the chief factor in its production, and solid fragmental material is the result; if on the other hand, it is quiet in its operation liquid rock, or lava, is the main product, and the gases play a less important role. We may thus roughly classify volcanic eruptions into those which are *explosive*, and those which are *quiet* in nature. When we attempt to classify actual volcanoes according to this difference in operation we very quickly find that while good examples of both types may be found, a very great number, perhaps the majority, are *intermediate* in their character, that is they sometimes erupt violently and sometimes give rise to quiet flows of lava. In many volcanoes during a quiescent stage there appears to be a gradual accumulation of pressure, the lava rises in the conduit, and eventually the eruption begins explosively, great quantities of gases mingled with dust and stones being ejected; the pressure being to a great extent relieved, this phase is succeeded by a quieter one in which the lava escapes through rents in the cone and forms outflows on its exterior.

Explosive Type. — In the most extreme form volcanoes of this type give rise to sudden, violent, and often extremely disastrous explosions. Enormous quantities of gas are suddenly projected into the atmosphere so thickly mingled with comminuted rock (dust and ashes) as to form vast out-rushing and expanding clouds of dense appearance and dark color. See Fig. 154. The greatest known explosion of this character occurred at Krakatoa, a volcano in the strait of Sunda near Java in August, 1883. After premonitory outrushes of gas for some time the great explosions occurred which blew away over a cubic mile of material from the volcano into the air in the form of dust and ashes. This vast dark cloud is stated to have risen 17 miles into the atmosphere, completely hiding the sun by its denseness over a vast area. The noise of the terrific detonations was heard over 150 miles, while the disturbance in the atmosphere was registered by barometers over the whole world. Vast waves, up to 100 feet above tide, were generated in the sea and rushed along the low-lying coasts of Java and Sumatra, sweeping far inland

Fig. 154. — Eruption of Vesuvius, April, 1906. Seen from Boscotrecase. The volcano is about 4000, the ash cloud over 17,000 feet high.

and destroying towns, villages and the lives of nearly 40,000 people; they were perceptible 3000–4000 miles away.

In May, 1902, from the volcano of Mont Pelée on the island of Martinique, and almost simultaneously from that of the Soufrière on St. Vincent in the West Indies, after small premonitory symptoms, violent explosive eruptions took place. No lava was outpoured, but the intensely heated gases were so thoroughly filled with incandescent particles of rock that the heavy, fiery clouds, not only rose but acting like liquids, rushed down the mountain slopes into the sea. Destroying all life in its course, the cloud on Martinique enveloped the town of St. Pierre and immediately destroyed it, together with its 30,000 inhabitants. On St. Vincent 2000 people perished and a broad tract of country was devastated. For many months after, Mont Pelée continued to eject at irregular intervals these incandescent clouds, one of which in Fig. 155 is seen rushing into the sea.

Fig. 155. — Fiery cloud of Mt. Pelee descending the mountain slope into the sea. The cloud at this moment is 7000 feet high, and moving forward at the rate of over a mile in 1.5 mins. A. Lacroix.

Intermediate Type. — Probably most volcanoes belong, or have belonged, to this class. In them the beginning of an eruptive period is likely to begin with explosive activity, manifested by the projection of gases in great quantity accompanied by solid fragmental material, bombs and ashes. In a succeeding phase liquid material issues; it may be projected by yet issuing gases, or it may break through the crater walls and produce outflows of lava, sometimes of great volume. Finally, the volcano becomes quiet, its energy for the time being exhausted; the lava may sink down in the conduit and a period of quiescence intervene before the next eruption. While this sketches in a general way the succession of events it must not be supposed that all volcanoes of this class are alike in the character of their eruptions, or that the same one always passes through a similar set of phases at each eruption, for there is great variability

in these respects. The main point is that volcanoes of this kind exhibit both explosive activity, and have also quieter outflows of liquid lava.

Vesuvius, the longest, and most studied, and, therefore, the best-known volcano in the world, belongs in this class. It occupies the site of an older volcano, which in the time of the Romans appeared to be extinct, for, although they recognized its nature, they had no traditions of its having been active. In the year A.D. 79, the volcano again became active in eruptions that destroyed the towns of Herculaneum and Pompeii on its sea-ward flanks. A great part of the former crater, on the side toward the sea, was blown away, or engulfed, and in its place the new center of activity, the modern Vesuvius began to build up. This has continued until the new cone is about 4000 feet high. Partly enclosing it lies the sickle-shaped ridge of Monte Somma, the remains of the older crater, Fig. 156. The volcano is in a state of almost constant, relatively, mild activity with irregular periods of violent eruption. The last great eruption occurred in 1906. From the nature of the material composing their cones it seems probable that the great volcanoes of the northwestern United States, previously mentioned and now quiescent or extinct, belonged in this class; as well as the active ones of Alaska and the Aleutian Archipelago.

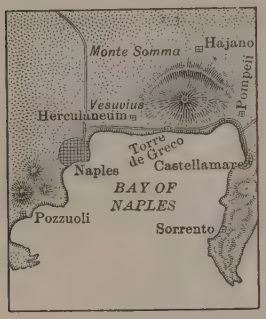


Fig. 156. — Map of Vesuvius and Vicinity.

Quiet Type. — These give rise to quiet outflows of liquid lava without explosive disengagement of gases and projection of solid material as dust, ashes and bombs. The lava in this case is very hot and possesses great liquidity. There is a more or less constant escape of gases from it, but without the catastrophic violence of the previous types. The best example of them is found in Hawaii.

The island of Hawaii consists of a vast mass of outpoured lavas surmounted by several cones, Mt. Kea, now extinct 13,800 feet high, Mt. Hualalai (8,300) active in 1801, and Mauna Loa (13,700) now active and some of whose lava flows have been 50 miles long. On the eastern slope of Mauna Loa, and about 20 miles from its summit, is the great crater pit of Kilauea, of a rudely oval form and 9 miles in circumference. Its rough stony floor of lava is the cooled and solidified crust resting on the top of the vast column of molten rock extending down to unknown depths in the earth's interior, Fig. 157. In some places it is not crusted over and here lakes of liquid lava, red to white hot and boiling from the escape of gases, may be seen. The depth of the crater floor below the edge of the rim varies according to the height of the lava column on which it rests; after a discharge it may sink down 700 feet, then through a period of years the lava gradually rises until it stands several hundred feet higher; owing to the increased pressure, and perhaps at a time when the elastic forces of contained vapors is unusually great, the conduit walls are ruptured and outflows of lava are produced. The lava column sinks down carrying the crater floor with it to a

lower level until equilibrium is established. Mauna Loa acts in a somewhat similar way, but the top of its lava column is nearly 10,000 feet higher than that of Kilauea. The outflows of lava are more apt to occur through the flanks of the mountain than through the crater rim; they sometimes take place below sea-level.

Fig. 157. — Floor of the great crater pit of Kilauea, Hawaii. To the left the view is obscured by vapors from a lava lake. J. S. Diller, U. S. Geol. Surv.

Relation between Volcanoes and Magmas. — The igneous fluids of the earth's interior, which give rise to volcanic action and volcanoes, are known as molten *magmas*. When these issue out on the earth's surface the liquid material, and the rock produced by its cooling and solidification, are called *lava*. It must not be supposed, however, that the composition which a solidified lava might show, if determined chemically, would be also that of the magma which yielded the lava. For the magmas contain in addition to the mineral substances of lavas great quantities of gases, especially water vapor, which are held in them under pressure in a kind of molten solution. As the magma rises to the surface, and the pressure is relieved, the gases escape, usually with more or less explosive energy, and give rise to volcanic activity. Since the different types of volcanoes, and of the lavas which they yield, depend in large measure on the magmas producing them, it is necessary at this point to consider the nature and composition of these molten masses.

Composition of Magmas. — As indicated above the substances composing the earth's magmas may be divided into two classes: *a*, those which when heated are *volatile* in their nature and for the most part escape as vapors and gases, such as water vapor, carbon

dioxide, hydrochloric acid, sulphurous vapors, etc., and which we shall consider in more detail later, and; *b*, those constituents which are *non-volatile* and remain to form the essential ingredients of the solid lavas. These are *silica*, SiO_2, and the oxides of six metals, *aluminum*, *iron*, *magnesium*, *calcium*, *sodium* and *potassium*. Silica in variable amount is always present in the magmas, but it has been found by chemical means, that, although some metallic oxides are always present, the particular kinds may vary from almost nothing to considerable quantities. Moreover, there is a kind of general rule about this; without going into details, which will be considered later under the heading of igneous rocks, it may be said that the magmas, which exhibit chemical gradations through the whole series, for consideration here and starting from the kind which is a mean and going either way in the series, may be divided into two classes, one in which silica, alumina (Al_2O_3) and the alkali metal oxides, soda and potassa, Na_2O and K_2O become more and more predominant, and the other in which, conversely, lime (CaO), iron oxides (FeO and Fe_2O_3) and magnesia (MgO) become higher. Lavas of the first class on cooling and solidifying may crystallize into a mass of mineral grains composed chiefly of alkalic-feldspar,* often with quartz, and are called *felsites*; in the second class alkalic-feldspar is subordinate and quantities of lime, iron and magnesia minerals, such as iron-ore, pyroxene, lime-feldspar, etc., are formed; lavas of this kind are termed *basalt*. Felsites are generally light colored, while basalt is very dark to black, and heavy from the iron minerals.

These characters and relations may be summarized in the following table:

Magmas consist of { *a*. Volatile substances; Gases and vapors, e.g. water, CO_2, etc.
b. Non-volatile substances; Constituents forming solid material, lavas.

		Chief constituents	*Chief minerals*	*Resultant rock*
Lava	*a*.	Much silica; alumina, alkalies.	Alkalic-feldspar, quartz, etc.	*Felsite*
	b.	Less silica; lime, iron, magnesia.	Pyroxene, lime-feldspar, etc.	*Basalt*.

Relation to Volcanic Eruptions. — The felsite lavas, or rather the magmas which produce them, are, even at very high temperatures, up to over 2000° C., thick viscous liquids, apparently from the high percentage of silica they contain, the amount being in some kinds as much as 75 per cent of the whole. For this reason the contained gases, when the magma rises into the upper part of the conduit and

* For description of these and other minerals see Appendix I.

the pressure is relieved, escape from them with difficulty and often with violence, giving rise to explosive eruptions. Hence the lavas which are found in volcanoes of the explosive type are apt to be of the felsite kind, as in Mont Pelée, or of kinds intermediate between it and true basalt, as at Krakotoa, Cotopaxi, etc. On the other hand the basaltic magmas, with about 50 per cent of silica, are very much more fusible and remain quite liquid down to much lower temperatures, probably 1300° C., the gases escape from them readily; but without explosive violence, as illustrated in the lava lakes of Kilauea in Hawaii. Thus quietly eruptive volcanoes yield basalt as a lava.

The above statement indicates the general rule; it does not mean that basaltic volcanoes never have explosive eruptions, for a basaltic magma may become cooled in the conduit and in consequence viscous and thus permit the escape of magmatic gases only with difficulty and explosive energy. Many examples of this might be mentioned. The explanation applies chiefly to the two extremes and indicates what is probably the most effective cause for the explosive and quiet types of volcanoes. The intermediate type of volcano may be due in part to the intermediate kind of magma, or to this combined with variations of viscosity at different periods, as well as variations in the supply of gases.

Products of Volcanoes

Gases. — It has been already shown that the products yielded by volcanoes may be divided into three general classes, gases and vapors, solid fragmental material, and liquid rock or lava. These may be now considered in more detail, beginning with the gaseous substances. The quantity of vapor discharged by active volcanoes is immense, and is indicated by the height and volume of the cloud with which many eruptions begin. This consists of the dust and ashes borne aloft by the uprushing column of gases. The great quantity of vapor thus discharged into the atmosphere by condensation may give rise to heavy downpours of rain in the vicinity of the volcano, while, owing perhaps to the friction of the particles and to atmospheric disturbance, the eruptions and rains are accompanied by striking electrical displays and lightning. Although it is not directly known what the composition of the gases is in volcanic eruptions, and it probably varies in different cases, from a quantity of indirect evidence it is assumed with good reason that it is chiefly water-vapor, or steam. As an instance of the quantity of water, which some believe is discharged, Fouqué estimated that from one of the subsidiary cones of Mount Etna there was discharged in 100 days a quantity of over 460,000,000 gallons in the form of steam.

Quite recently some geologists, basing their opinions largely on the experiments and ideas of Brun, have suggested the view that water-vapor is of minor importance, or wanting, in volcanic phenomena. But the investigations of Day at Kilauea refute this and show that water escapes from even this quiet basaltic magma in considerable quantities and that, by means of iron pipes suitably placed, it could be collected directly from it.

In addition to the water, the different kinds of gases and volatile products exhaled by volcanoes would make a long list. Not only are these given off from the vent itself, but the outflows of lavas, for weeks and even months, after their extrusion continue to emit them as they cool and harden. It appears that in the vents and from the hottest lavas, hydrochloric acid, hydrofluoric acid, and even hydrogen are given off, and to the mixture of the latter with oxygen and its combustion are ascribed by some the explosions in the conduit. Various compounds of sulphur are emitted by some, but not all, volcanoes, such as sulphuretted hydrogen, H_2S, and sulphur dioxide, SO_2. In declining stages of activity, and in less heated areas, carbon dioxide appears to be one of the chief products. Nitrogen and boric acid, H_3BO_3, may also be mentioned. Although little is known concerning the chemical conditions of these substances in the magmas, the knowledge of their presence, and what we have so far been able to learn about them, are of great value and interest in its bearing on important problems in geology, such as the origin of hot springs and geysers, contact metamorphism, and ore deposits, as we shall see later.

Fragmental Products. — These are the materials blown into the air by the sudden liberation of the gases. They may be derived from the crust, or plug, of hardened lava left in the upper part of the conduit from a previous eruption, or of rock material torn loose from its walls, or of lava projected from the upper part of the liquid column by the violent expansion and expulsion of gases from the magma by relief of pressure as it rises to the surface. In the latter case, although the material may start in its aerial flight in a liquid condition, it generally hardens in its passage and falls in solid form. The pieces of rock, and the particles of magma driven upward and solidified, are of all dimensions from dust so fine that it may float in the atmosphere for several years to large masses of several hundred pounds in weight. According to size it is roughly classified as follows; pieces the size of an apple, or larger, are called *bombs;* those the size of a nut are termed *lapilli* (meaning little stones); those the size of peas, are volcanic *ashes*, while the finest is *volcanic dust.* The ashes and lapilli are frequently spoken of as *volcanic cinders* and cones made of them as cinder cones. It should be clearly remembered, however that while these terms are used to describe the appearance of these products they are not the result of ordinary combustion. An example of a volcanic bomb is seen in Fig. 158.

The objects described above are in part composed of compact solid rock and in part are apt to have a spongy, cellular, or vesicular character. This latter is

due to the fact that while the major part of the gases are passing into the air, and carrying the fragments with them, a minor part is expanding in the particles of liquid, puffing them up into the cellular forms. While the bombs, lapilli, and most of the ashes fall in the immediate vicinity of the vent, and thus help to build up the cone, the dust may be carried long distances, hundreds of miles or more, by the prevailing winds, and be thus spread over an immense area. Huge quantities are discharged in great eruptions, amounting to many millions of tons. Such dust showers may be very destructive to vegetation, and even to animal life, but the soil ultimately yielded by them is very fertile. See Fig. 154.

Fig. 158. — Volcanic bomb, Lipari Islands.

Liquid Material; Lavas. — In volcanoes whose periods of eruption begin explosively the liquid lava generally issues later, after the vent has been cleared. The cone is not a structure of great strength and is liable to be ruptured, or fissured, by the explosions and the pressure of the lava column, and hence the outflows are not apt to take place over the lip of the crater, but to issue through fissures in the side of the cone. It may even happen, especially when the cone is composed of cinders, that, unable to withstand the pressure, one side may give way, allowing a flood of lava to rush out from the breach thus made.

The appearance and character of a lava stream, and the material produced by its solidifying, depend on several things; on the chemical nature of the magma, on the degree of viscosity of the molten fluid, and the extent to which it yet retains dissolved gases. On the chemical composition will depend the nature of the rock, whether it will be a light-colored felsite, or a black basalt, or something intermediate, as previously explained. On the viscosity will depend the rate at which lava will flow, the distance to which the stream will extend, and in large measure the appearance its surface may present. When it issues, the lava is red, or even white-hot. It soon cools on the surface, darkens, and crusts over. If very viscous the under part may yet be in motion, the crust breaks up into a mass of rough, angular, jagged blocks of rock which are borne as a tumbling, jostling mass on the surface of the slowly-moving flow. When, eventually, the latter comes to rest and hardens, the lava field produced is extremely rough and difficult to traverse. See Fig. 159. Such lava fields in Hawaii are called *aa* by the natives.

Fig. 159. — Rough surface of an advancing lava flow; *aa*, lava. Vesuvius.

Fig. 160. — Flow of basaltic lava running down a stream bed, the water of which is turned into steam. This lava, if cooling as seen, would have the pahoehoe surface. Hawaii. J. S. Diller, U. S. Geol. Surv.

On the other hand very liquid lavas, like those of Kilauea and Mauna Loa, may harden with much smoother surfaces which exhibit, however, curious ropy, curved, wrinkled, or twisted and billowy forms, as seen in Fig. 160. Lava surfaces of this kind the Hawaiians term *pahoehoe*.

Very liquid lavas may move with considerable rapidity, up to, perhaps, ten miles an hour, depending on the slope, Fig. 160; as they cool and become viscous the motion may be almost indefinitely slow; the stream creeping onward possibly for several years.

Sometimes on slopes, after the lava has crusted over, the liquid portion beneath may run out from below, leaving beneath the hardened surface long galleries, tunnels, or caves. On some cones the natural downward drainage may pass into these, disappear from view, and issue again below in the form of springs. This may be, in part, the cause of the springs around Mount Shasta.

In some cases the magma, or lava, ejected is too viscous to flow; it may then pile up in a great dome on the surface. This is chiefly, if not wholly, confined to the felsite varieties of lava. Domes of lava have been observed in Central France, Bohemia, Germany, etc., and are thought to have been formed in this way. They probably exist elsewhere. After the violent eruptions of Pelée, in 1902, had cleared this orifice the column of felsite lava that was pushed up was so hardened into rock that it rose like a vast tower into the air above the volcano, until it attained a maximum height of 1000 feet. See Fig. 161. Gradually it crumbled from explosions of gases into a mass of blocks.

Fig. 161. — Rock tower of Mont Pelée, Martinique. 1000 feet high. A. Lacroix.

Effect of Contained Gases; Vesicular Lava.—That the lavas, even after their issuance, still contain dissolved gases is abundantly shown, not only by the clouds of steam which may issue for weeks and months from them, but also by the structures which they assume as they cool into stone. Thus the upper part of the flow, especially in viscous lavas of the felsite class, may be so puffed up by the innumerable bubbles of vapor in it, expanding on relief of pressure, that it may assume the

character of a glassy froth. Such rock froth, which is usually white or light colored, is known as *pumice* or *pumice-stone*.

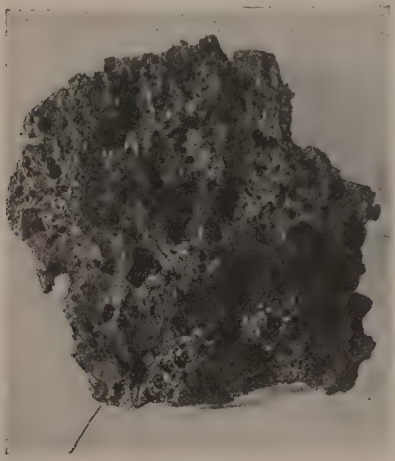


Fig. 162. — Volcanic scoria.

In more liquid lavas, especially those of the basalt class, the bubbles are larger and the rock has a spongy, cellular, or vesicular character. These porous, cindery, or slag-like forms are called *volcanic scoria*. They are usually dark to black, or reddish. See Fig. 162.

Pumice, scoria, and vesicular forms are characteristic features of the upper surface of lava flows, and they constitute also a major part of the coarser fragmental material, such as bombs and lapilli, which helps to make the cone. See page 192.

Crystallization of Lavas; Glass and Stone. — After lavas have been poured out and have solidified they usually present the ordinary appearance of *stone*, but sometimes, instead, that of *glass*. The reason for this seems to be as follows. If the liquid is not too viscous the chemical molecules composing it will have capability of motion and will arrange themselves into definite compounds, that is, will crystallize into mineral grains, or crystals. It may be that the crystal grains are large enough to be readily seen and the kind of mineral determined, or they may be so minute that the lava has a homogeneous appearance; nevertheless if crystallization has taken place the lava has the aspect of stone.

On the other hand, if the lava is extremely viscous, or quickly becomes so through rapid cooling, the molecules may not be able to arrange themselves, or crystallize, into minerals and the mass solidifies as a homogeneous substance, that is, as a glass.

Thus while lavas ordinarily, in hardening into rock, adopt a stony aspect, under certain conditions they may assume glassy forms. This occurs chiefly with felsite lava, for, as previously explained, this kind is usually the more viscous. Volcanic glass is called *obsidian;* less commonly, in allusion to its luster and appearance, pitchstone.

In some cases the obsidian is pure glass, in other ones a mixture of glass and crystals. In the Yellowstone Park, Obsidian Cliff presents a section of volcanic

glass 100 feet thick, which has cracked into columns in cooling. Such a thickness of purely glassy lava is unusual. It is chiefly on the edges and upper surface of lava streams that these glassy forms are found. Primitive peoples, before they gained a knowledge of metals, made much use of obsidian for making knives, arrow and spear points, etc., in a manner similar to their use of flint.

Varieties of Volcanic Cones and Craters

Kinds of Cones. — The nature of a volcanic cone depends on the kind of material of which it is built. If composed wholly of fragmental products it will be very high and steep in proportion to its size because the fragments fall around the vent as solid pieces, and the angle of slope is that of the angle of repose for such broken rock pieces. Moreover, as lapilli and volcanic ash are very angular, rough and clinging, slopes of 40 degrees may be attained without sliding of the accumulating mass. Cones of this kind are often

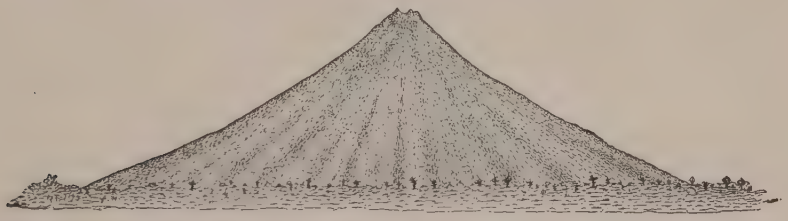


Fig. 163. — Cinder cone, showing steep angle of repose of lapilli. Outline as given by a photograph of Mayon volcano in the Philippines.

called *cinder cones*, and they are characteristic of volcanoes of the explosive class, Fig. 163. In contrast with them *lava cones*, formed entirely by quietly outflowing liquid lavas, like that of Mauna Loa, and shown in Fig. 160, are necessarily very low and flat in proportion to their size, the angle of inclination being less than 10 degrees. See Fig. 164. These belong to the quiet types of volcanoes. Most vol-

Fig. 164. — A lava cone, to show contrast with Fig. 163. From the Snake River plain, Idaho.

canoes, however, and this includes the greater part of the largest ones in the world, are of the intermediate type in their eruptions and in consequence their cones exhibit a form intermediate between those just described. For they are built up, sometimes by the fall of ashes and lapilli when they are explosively active, and sometimes

of lava flows when the eruption is quieter. This is the character of the great cones of the Pacific States, Mounts Shasta, Hood, Rainier, etc.

In the larger volcanoes the eruptions which often break out on their lower flanks give rise to smaller, subordinate, or 'parasitic' cones. Mount Etna is surrounded by over 200 of these, some of which are nearly 700 feet high. San Francisco Mountain in Arizona, an extinct and partly eroded volcano, exhibits a number of such minor cones, some of them remarkably well preserved. As an active volcano grows the earlier parasitic cones may be buried and concealed under later accumulations, or, in declining stages of activity, the eruptive energy may show its last efforts in the formation of them, as appears to have been the case at the San Francisco volcano, just mentioned.

Calderas; Explosion and Subsidence Craters. — The term caldera, from the Spanish for caldron, is applied to craters of great size, especially those which are very broad as compared to their depth. The name is taken from the huge crater in the Canary Islands, called La Caldera, which is from three to four miles wide and faced inwardly by lofty cliffs 1500 to 2500 feet high, except on one side where the wall breaks down to the sea. From without, at a distance, the general aspect is that of a huge cone broadly truncated. Many examples of such great craters are known in various parts of the world, and a study of them has led to the view that, in some cases, they have been caused by gigantic explosions which have blown away a great part of the original cones as dust and ashes, leaving the calderas to mark their sites, or, perhaps more generally, that they have been produced by the subsidence of the column of liquid lava, leaving a great cavity which the central part of the cone subsided into and more or less filled up, the remnant of the cone outside making the caldera, or to a combination of these two causes.

Thus Krakatoa in its explosive eruption of 1883 previously alluded to appears to have blown away a good part of the original volcano and to thus suggest how part of the calderas are formed, although it is possible that another part may have been engulfed by the subsidence of the lava. The remnant left may mark the site of a partial caldera. The best instance of a caldera in the United States is found in Crater Lake in southern Oregon. This lake occupies a caldera at the summit of a broad sloping volcanic mountain in the Cascade Range, and is about six miles long by four broad, 2000 feet deep and encircled by steep cliffs 500 to 2000 feet high, Fig. 165. An island in it made by a small but perfect cone of volcanic material indicates a feeble renewal of activity after the principal subsidence. The caldera if emptied of its water would appear as a great basin. The reason for believing that the caldera was formed by subsidence of the lava column and engulfment of the greater part of a former cone rather than by explosion lies in the existence of glaciated valleys leading up the outer slope of the mountain until they abruptly end as notches in the cliff wall, and in the absence of the débris which an explosion would have spread over the ad-

jacent outer slopes. The former mountain, to which the name of Mt. Mazama has been given, is conceived to have had about the size and general character of Mt. Shasta and during the glacial period it was heavily capped with snow and glaciers.

It may be noted here that many craters and calderas of extinct or resting volcanoes are filled with water, giving rise to lakes.

Fig. 165. — Part of the basin and wall of Crater Lake, Oregon. Note the small cone within. J. S. Diller, U. S. Geol. Surv.

Explosion Craters. — It has happened in some cases where volcanic activity has begun that it has proceeded no further than the initial explosions which have forced a vent through the country rock. The material blown out may make a low slight ridge around the crater, but no real extensive cone is built up. Sometimes volcanic products such as pumice, cinders, etc., are mixed with the fragments of the country rocks. Such basins may be from a few hundred feet to several miles in width, and in humid regions they are usually filled with water and form crater-lakes. Some of the best examples of them are found in the region west of the Rhine in Germany, known as the volcanic Eifel. They are there called *maars* (German, maaren), like the Pulvermaar, etc. A crater which strongly resembles a maar exists at Coon Butte in Arizona. The basin sunk in the plain is about 3/4 of a mile in diameter and 500 feet deep. The presence of meteoric iron in and about it, and other features, have led to the view that it was caused by the impact of a huge meteorite, and is probably not of true volcanic origin.

Rebuilt Volcanoes. — Not infrequently it happens that after a caldera has been formed, either by subsidence, or by explosion, or both, that a renewal of volcanic activity starts building up a new cone within it. This is shown on a small scale at Crater Lake just mentioned, but one of the best examples of this is seen in Vesuvius, which has built itself up in the old crater ring of Monte Somma, as explained on page 188. From this rebuilding within the older crater wall there results a *cone in cone* structure, of which there are many examples. The vast crater-like pits, which are so common on the surface of the moon, frequently show this arrangement, suggesting

an analogous origin for them. It is conceivable that Vesuvius, before it becomes extinct, may go on increasing in size until the old caldera is obliterated; in this case it would be a completely *rebuilt volcano*.

Structure and Dissection of Volcanic Cones

Structure of a Composite Cone. — If a column of molten magma be forced upward through the superficial crust of the earth until it reaches the surface the relief of pressure will enable it to commence discharging its dissolved gases and vapors. It may be that the pressure of the contained gases is too great for the last upper layers of bed-rock to restrain until the magma reaches the surface, these rocks may be blown into the air and a vent drilled ahead of the rising column of lava. Arrived at the surface an outflow may take place quietly, or, if the magma is too viscous for this, explosions may continue and material be blown into the air. By the falling of the fragments the cone is built up, somewhat as seen in the diagram,

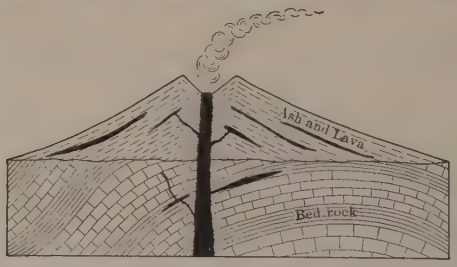


Fig. 166. — Ideal section through a volcano. The dark layers in the cone are buried flows or injected masses.

Fig. 166. The pieces cannot, of course, fall back against the uprushing column of gases and cover the vent; they must fall outside of this, the heaviest and largest first and nearest to it, the smaller and lighter later and farther away, the distribution of the latter depending much on the wind. Thus the cone builds as a circular ridge upon whose crest is the heaviest deposit of material which tends to roll and slide both ways, outwardly away from the center and inwardly down the crater toward the vent. This forms the cone and crater, and certain features regarding their structure follow as a sequence of this mode of formation.

Tuff and Breccia. — The deposits of successive eruptions will be marked by layers, some of coarser, some of finer material, in each of which, if not composed of uniform-sized particles, there is a gradation from coarser at the bottom to finer at the top. Thus there arises a rude stratification, or bedding, the beds sloping down and

out from the crater edge, Fig. 167. The bombs, lapilli, and ash composing them gradually become compacted by their weight, and by the infiltration and deposit of cementing substances, into a more or less friable, porous rock called, when composed of the coarser materials, *volcanic breccia*, and when of the finer dust and ashes, *volcanic tuff*. In the crater the fragments are larger, often large blocks of rock, and they usually form a tumultuous, mingled mass without order or arrangement, filled in with finer material, the whole called volcanic *agglomerate*.

Fig. 167. — Inclined beds of volcanic ash. Part of a former cone at Trinchera, Colo. W. T. Lee, U. S. Geol. Surv.

Lava Flows and Dikes. — In addition to the beds of tuff and breccia there are in most volcanoes flows of liquid lava down the outer slopes of the cone, as previously described, and as these harden into solid rock they help to protect the softer layers of tuff and breccia from erosion, and to give strength to the mass. Since the lava rarely overflows the crater, but, especially in high cones, breaks through fissures, or rents, lower down, these latter also become filled with lava which hardens into rock. These rock-filled fissures are called *dikes*, and like ribs they also serve to strengthen the structure. Thus a vertical section through a volcano, as shown in Fig. 166, shows a central core of magma surrounded by beds of tuff and

breccia mingled with flows of lava, which are cut in a general radial direction by dikes. This discussion gives us an idea of the general structure of a typical cone, one formed by the intermediate type of volcano; there are, of course, many variations from this, as may be inferred from what is previously stated.

Dissection of Volcanoes. — At every stage of its existence a volcano is subject to the agencies of erosion and weathering, which tend to cut down all prominences on the earth's surface. Its height and appearance at any given time is the result of the balance between these forces and the upbuilding one of vulcanism. Even active and growing volcanoes are commonly trenched and scored by ravines and gulches. After eruptions, when the cones are covered with fresh deposits of dust and ashes, the latter become so saturated with

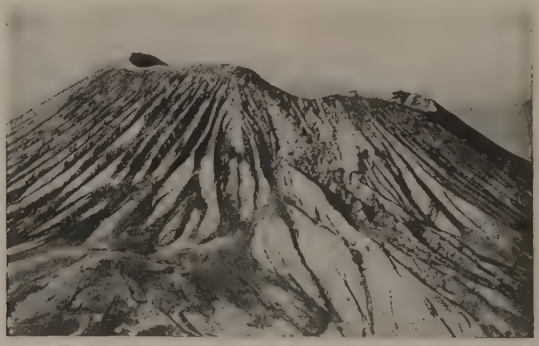


Fig. 168. — Vesuvius in 1906, showing trenching by ravines, in the ashes after the great eruption. Photo by F. A. Perret. (Courtesy of Harper's Weekly.)

water from the rainfall that they may give way in places and slide down as flows of liquid mud, leaving ravines, which are enlarged by subsequent storms. See Fig. 168.

As soon as a volcano becomes extinct the ravages of erosion are unchecked and the period of dissection ensues. The lighter tuffs and breccias are carried away more easily and rapidly, the harder, more compact and resistant flows and dikes of lava, and the parts protected by them, more difficultly and slowly. It is, however, often surprising how long a time cones composed of mere cinders loosely piled will resist erosion and retain their form; the reason for this appears to consist, partly in the clinging character of the rough fragments, and partly in their porosity, which allows the rainfall to sink through without causing downwash.

As erosion progresses, the mass of rock formed by the solidification of the magma in the central conduit is likely to be brought to view,

provided the magma column was not withdrawn before the volcano became extinct. In the latter case, the site of the vent will probably be marked by a mass of agglomerate. With continuing erosion and the disappearing of the cone, the central rock mass, owing to its greater resistance, is liable to form a decided prominence, and, even when erosion has finally swept away all external evidences of the cone and bitten deeply into the underlying rocks, it may remain projecting, a monument to the vanished volcano. A rock mass of this kind filling a former conduit is termed a *volcanic neck*. See Fig. 169. Here we must pause, for this carries the dissection of the volcano to its very root.

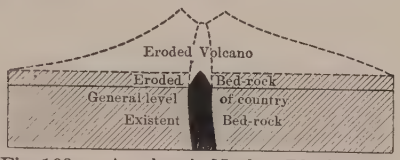


Fig. 169. — A volcanic Neck. Black shows mass of volcanic rock projecting through erosion above general level of country.

Extinct volcanoes are found in every quarter of the globe and in great numbers of regions where volcanic activity has long since disappeared. Every stage of dissection is represented among them from cones only slightly worn to those so thoroughly eroded that the original shape has been entirely lost, but whose central rock core, outlying concentric masses of lavas, tuffs and breccias, and radial dikes still plainly show their former existence. The general region of the Rocky Mountains, once a theatre of active vulcanism, is now strewn in many places with the wrecks of former volcanoes. A good example of this is found in the Yellowstone Park and surrounding country where, as we shall see later, the spark of vulcanism still lingers. So deeply eroded are the volcanoes that their remnants now form a region of most varied and irregular topography.

Life and Distribution of Volcanoes

Age of Volcanoes. — We have very little knowledge of the length of time represented by the life of active volcanoes. Undoubtedly it must vary greatly in different individuals. We know, for example, that Etna has had the same general character for the last 2500 years. We can only be sure that the piling up of such vast masses of material as are represented in some of the great volcanoes must have required, from the human standpoint, a vast lapse of time. On the other hand, we know, by a variety of considerations, that the present active volcanoes are, from the geological standpoint, recent affairs, a fact which indicates to us in one way the great length of time involved in the past history of our earth.

It is also difficult to say when a volcano is extinct, for long periods, hundreds of years, may elapse between eruptions. In the Middle Ages, Vesuvius had been so long dormant that its crater was filled with vegetation and gave no sign of life. But in 1631 it became violently eruptive and has since been intermittently active.

New Volcanoes. — Within the period of recorded human knowledge a number of volcanoes have begun their existence and many of them are still active. Vesuvius is, of course, the most noted case of this, but other examples are seen in Jorullo in Mexico, which came into being Sept. 28, 1759, in the midst of a cultivated plain and is now about 4,300 feet high, and in Izalco in Salvador which began in 1770, has been almost continuously active since then, and is now over 6,000 feet high.

No well-authenticated instance of a volcanic eruption is known to have been witnessed within the limits of the United States proper since the settlement of the country. That such may have happened recently at Lassen's Peak in northern California is possible. What appears to be the latest volcano in the United States is found in a cinder cone in the neighborhood of Lassen's Peak. See Fig. 170. It is 640 feet high above its base with a crater about 750 feet

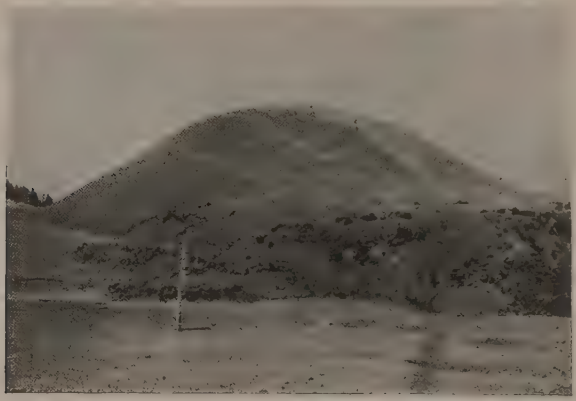


Fig. 170. — Cinder Cone, near Lassen's Peak, Cal. J. S. Diller, U. S. Geol. Surv.

in diameter across the top and 240 feet deep. After the cone was formed a large flow of basaltic lava burst from it and nearly filled a lake upon whose border it was situated. It then, apparently, became extinct. From the trunks of trees still standing, which were killed by hot ashes at the time of its early eruptions, and from the age of those now growing on these ashes, it is inferred that the volcano began somewhat over 200 years ago. The outflow of basalt was considerably later.

Distribution of Volcanoes. — A study of the distribution of volcanoes over the world shows that, if we consider the present active vents, perhaps 500 in number, and those cones which have suffered so little erosion that they may be considered dormant, or only recently extinct, of which there are several thousand, they have a general tendency to be grouped in long lines upon the earth's surface. The most marked one of these is the great zone which borders the

Pacific Ocean; it passes northward along the Andes, through Central America into Mexico, through the United States and Canada to Alaska, then along the Aleutian chain to Asia, and turning southward through Kamskatka, Japan, and the Philippines it crosses the East Indies, and by various island chains again passes into the Pacific. Certain portions of this belt, like the Andes and the Aleutian chain, are remarkably linear and well developed. Another great general zone has an east and west direction, from Central America

Fig. 171. — Map showing distribution of active or recently extinct volcanoes in the Eastern Hemisphere. On S. L. Penfield's stereographic projection.

through the West Indies; it is then continued through the Atlantic by the Azores, Cape Verde and Canary Islands, runs through the Mediterranean, through Asia Minor and Arabia, and is continued by the long chain of the East Indies, where it crosses the previous one, out into the Pacific. This linear disposition occurs not only on a large scale, affecting series of volcanic groups, but on a small one as well, influencing the distribution of the volcanoes composing

the individual groups. It may be studied by referring to Figs. 171 and 172.

Volcanoes are found both on the continents and in the oceans, most, but not all, of the oceanic islands being volcanic. Notably in the Pacific there are great numbers of them, many extinct or dormant, some still active, and here again in many cases they are grouped in lines, and stand on the submarine ridges which rise from the ocean floor. From this fact of linear arrangement has been

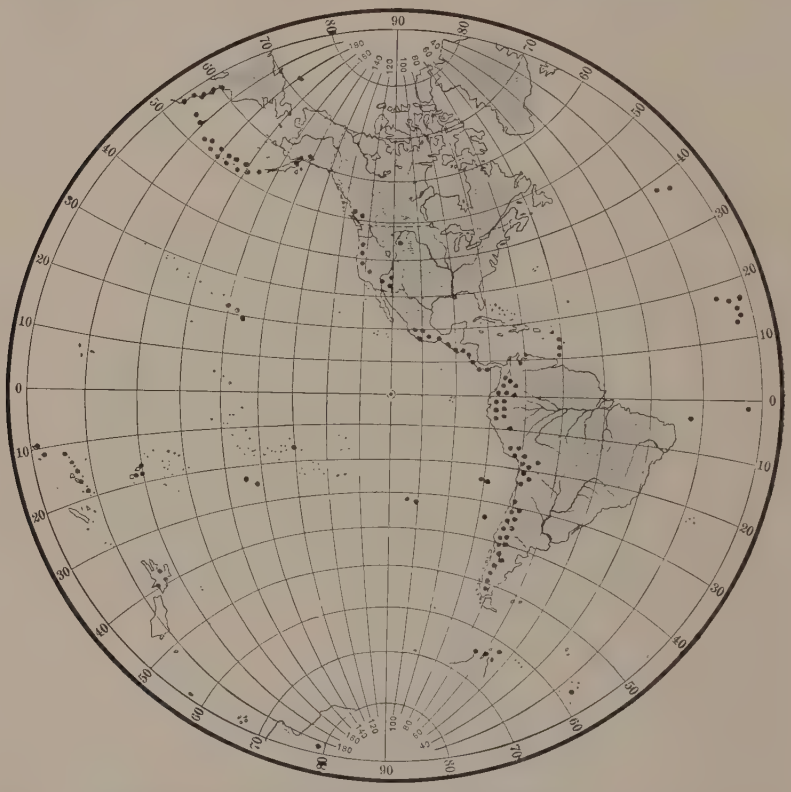


Fig. 172. — Map showing distribution of active or recently extinct volcanoes in the Western Hemisphere. On S. L. Penfield's stereographic projection.

drawn the important deduction that volcanoes are in general situated on or near lines of fracture, folding, and weakness in the earth's crust.

The idea of the connection between volcanoes and fracture lines in the earth's crust has in many cases been pushed too far. Undoubtedly lines of fracture and weakness have proved favorable sites for volcanic action, not only for a time, but in places for long-continuing geologic periods, and this has greatly in-

fluenced their origin, situation and arrangement. But on the other hand, it seems clear that a volcano, or a group of them, may originate where no definite connection between them and any fracture line can be shown to exist. And in places no tendency to a linear arrangement in the group may be seen. It appears that the volcanic forces in such cases were sufficiently powerful to find an outlet without needing the aid of a fracture. A good example of this may be seen in the Highwood Mountains, a group of extinct and greatly eroded volcanoes situated on the great plain of central Montana. While the remaining tuffs, breccias, lava flows and dikes, composing this group, and their arrangement and attitudes, show clearly the cones that once existed, erosion has dissected them so deeply that the shapes of the cones have been lost, the central conduits now filled with the massive rock are exposed, and their relations to the sedimentary bedded rocks through which they were forced laid bare. There is no evidence of any profound breakage or displacement of the crust on which they could be placed, nor do the conduits show linear arrangement.

A striking instance of how little influence favorable disposition of surface topography may have in determining the site of volcanic action, which in the immensity of its power appears to disregard such minor considerations entirely, may be seen at the Grand Canyon of the Colorado. Uninfluenced by its 5000 feet or more of depth, volcanoes have broken out upon its very rim, instead of in its depths, and their lavas have flowed down into it, thus showing also their recent origin compared with that of the canyon.

The fact that almost all active volcanoes are either situated in the sea, or in a general way around its borders, and when inland are in, or near, lakes has led many to believe there must be a necessary connection between the surface waters and the cause of volcanic activity. This question will be considered later in the discussion of the origin of volcanoes.

Submarine Eruptions. — From the great number of volcanic islands in the sea, most of the oceanic islands being of this nature, it is evident that in times past tremendous eruptions and vast outpourings of lava have occurred on the sea floor. The volcanic chain of the Hawaiian islands is an example of this. Instances of actual eruptions beneath the sea have been observed in a number of cases and recognized by the issuance of vapors, ashes, etc., from the water. Thus, in 1831 a volcano was thrown up in the midst of the Mediterranean Sea, forming a new island called Graham's Island. Being composed of light cinders it was soon cut off by the waves and reduced to a shoal. The three Bogoslov volcanoes of the Alaska-Aleutian chain formed in 1796, 1883, and 1906 are other examples. Such eruptions have occurred repeatedly in the past and their products, mingled with sediments from the land, have been laid down as deposits on the ocean bottom, as seen in many places where the sea floor with these deposits has since been raised and become a land surface. Nor do these volcanic products differ in their essential characters from those which have been described as formed by volcanoes upon the land. It also seems probable that many of

the cones formed beneath the sea and thus protected from erosion are of great age, even quite old from the geological standpoint, and have served as the base for coral islands, as previously described, page 173.

Fissure Eruptions. — In several regions outflows of lava have taken place on such a gigantic scale and cover such widely extended tracts of country that it is commonly believed they cannot be referred to the outpourings of any volcanic cone or group of volcanoes. Moreover, the cones from which they might have come are apparently wanting. It is thought that these great lava-floods have issued from fissures in the earth's crust. The result is that broad plains, or plateaus, consisting of successive level sheets of basalt lava, sometimes interlaid with beds of tuff, have been formed. Instances are found in the great lava fields of the Columbia and Snake rivers in the far Northwest of the United States, which cover from 150,000 to 200,000 square miles, and are in places 3,000 feet deep, which are shown on the geologic map in Part II of this work; in the so-called Deccan traps of western India which are stated to be 200,000 square miles in extent and to reach a maximum thickness of 6,000 feet; in the north of the British isles, which in part, with the outlying island groups, appear to have been carved by the sea from a great basalt plateau, which may have extended to Iceland. The level character of these lava sheets is evidently due to the extremely thin liquid nature of the issuing magma, which permitted it to run for many miles before congealing. Thus in Iceland, a lava flow has been traced a distance of 60 miles. It is such outpourings, which occur in other regions as well as in those mentioned, which exhibit to us the grandest effects of vulcanism. It is a conservative estimate to say that, since a comparatively recent geologic period, as much as 500,000 cubic miles of molten material have been transferred from the inside to the outside of the globe by the extrusive process of vulcanism, most of it in the manner here described.

It should be mentioned in this connection that those geologists who have most closely studied the great lava plains of the Snake River do not believe that the molten material issued from an extensive system of fissures, but from various vents, like those of ordinary volcanoes of the quiet type, some situated along the sides of the enclosing mountain chains, others on the plains themselves. The lava craters which mark the site of the vents are, for the most part, so extraordinarily low and broad as to escape detection in a general view and are only found by closer observation, compare Fig. 164. This is due to the extremely liquid character of the lava which spreads out in streams 50 miles long and many miles wide. Through repeated outpourings of this kind the previous topography was buried and the plains produced. It may be that other lava plateaus, referred to above, were made in a similar way.

Origin of Volcanoes

General Remarks. — So far as regards the nature of volcanoes, the character of their eruptions, and of the products afforded by them; their distribution and in some measure their life, we are dealing with ascertained facts. We also know quite clearly the reason for the different kinds of eruption and varied types of cones. But when we seek to learn the cause and origin of vulcanism we must then consider the depths of the earth itself, about which we know very little. We are led from facts into almost pure speculation, and this should be clearly understood by the student. It is evident that our ideas of the cause of volcanic action will depend upon those which we have concerning the nature of the earth's interior; what has been learned regarding it will be considered in a later place. There are, however, certain phases of it which may be considered here.

Problems of Vulcanism. — Some important questions that arise when we seek to discover the cause of vulcanism may be stated as follows. What is the origin of the *heat* which keeps the magmas in a molten condition? What is the origin and history of the molten *magmas* which come to the surface? From how deep down do these magmas come and where is the seat of vulcanism? What is the origin of the *gases* and vapors; have they always been contained in the magma, or has it absorbed them from outside sources, and, if so, when and where? And finally, what causes the magma to *ascend* to the surface from depths below and thus give rise to volcanoes? These are fundamental problems, most of which our knowledge, at the present time, is too limited to enable us to solve. Views held regarding them may, however, be briefly stated and discussed.

Origin of the Heat. — At the present time the most prevalent view regarding the source of the heat demanded for the molten magmas is that it is original, the remains of a globe once highly heated and still intensely hot in its interior. Many, however, do not share this opinion, but regard the heat as due to the gradual contraction and compression of the earth through the force of gravity, a process which should cause a gradual flow of heat outward toward the surface, which by its concentration in particular regions induces melting and the formation of masses of magma. We are not yet in a position to decide definitely between these views.

It has been urged by some that the crushing together of the earth's outer shell through contraction must generate heat on an enormous scale. It is pointed out that such compression and crushing have taken place in the formation of moun-

tain ranges, as we shall see later, and it is inferred that through this process melting has occurred and volcanoes have been made. There are two objections to this view. The first is that volcanoes are often found where there has been no crushing of the outer crust, or at least, not for an immense period of geologic time antedating the appearance of the volcanoes, as at the San Francisco Mountain and other volcanoes on the high plateau in Arizona. The other is that the folding and compression of the earth's crust which make mountain ranges is a very slow process, and, although great quantities of heat would undoubtedly be generated, it has not been shown why it would not be as rapidly dissipated, or transformed in doing chemical work. How could it become accumulated and concentrated sufficiently to produce melting and volcanoes? For, to use an illustration, what we need is not a cask of warm water, but a cupful of boiling water.

Since the discovery of radio-activity, and the researches upon matter which it has induced in these later years, have shown that some elementary substances are disintegrating and breaking down into other substances, as for example, uranium into radium, helium, etc., and radium into helium, lead, etc., with production of heat in notable quantity, it has been assumed by some that changes of this nature are going on within the earth and that in this way the heat necessary for volcanic action is produced. It is pointed out as a proof of this that volcanic regions and lavas show a content of radio-active substances. There is wide diversity of opinion on the subject and, at present, this view has not advanced beyond the speculative stage.

Origin of the Magma. — This is evidently closely connected with the origin of the heat, as just discussed. The prevalent view is that the magma is a remnant of the original molten substance of the globe. Those who hold this view do not, however, necessarily claim that it has always been in a liquid condition. In melting, rock material must expand; if sufficient pressure be put upon it, it cannot expand and, therefore, cannot melt. It is assumed, with the tremendous pressure reigning in the earth's depths, the material although very hot would be solid, but should relief of pressure come in any place, as for instance, by upward buckling of the earth's crust, or by long erosion reducing the pressure, or by both, then melting would ensue and a body of magma would be formed. A view, once held, was that the lavas are produced by the fusion of deeply buried sediments, but for a number of reasons, this idea now receives little credence.

Another theory which has been advanced is that the melting of the rock material is due to the issuing of superheated gases, squeezed out of the deeper, inner portions of the earth's interior by its gradual contraction from cooling. They are supposed to melt the rocks on their upward passage, and thus give rise to the magma and to volcanic action. The difficulty in this view lies in the enormous quantities of gases that would be required to melt rocks and produce

large bodies of magma, and that the gases under pressure tend to go into solution in the magma and become inert. And so, like the origin of the heat, that of the magma must for the present be considered unsettled.

Origin of the Gases. — In regard to this, opinion has been divided into two classes, one that believes that the gases, as indicated in the preceding paragraph, were originally contained in the

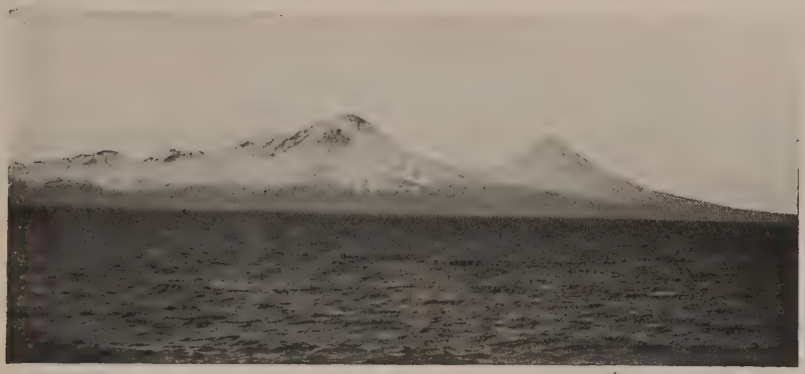


Fig. 173. — Pavlof Volcano, Alaska. G. K. Gilbert, U. S. Geol. Surv.

earth, which has been gradually losing them, and another that they have been absorbed by the magma, especially the chief gas, water vapor, from surface waters descending through the crust. The former appears, from several considerations much the most probable view and is the one mostly held at this time.

The fact that most volcanoes are situated in, or near, the sea or lakes has been considered a strong proof that the water-gas contained in the magma has been obtained from descending surface waters. But this argument when examined loses its force. The nearness of some volcanic chains to the sea, like those of North and South America, is only relative to the size of the continental masses. Actually they are long distances inland; in South America from 100 to 250 miles and this includes some cones still active, like Cotopaxi, which are not near any inland water body; in North America from 30–100 miles or more, and although these are mostly extinct it can yet be shown in many cases that when active there was no body of water near them. And the volume of steam, from even small volcanoes at periods of eruption, is sometimes so enormous, as has been previously shown, page 191, that we cannot attribute it to ordinary rainfall or surface water, leaking downward through the rocks. Moreover, if the magma obtains its water from surface supply it must do so in the very upper part of the crust, since, as already shown, below this the openings which permit of water supply and circulation in the crust are closed up. But several considerations show us that at such shallow depths, far from absorbing water, the tendency of the magma is to get rid of it with great energy and finally with terrific force. And if the magma absorbed such enormous quantities of water and converted

it into steam it is difficult to see why it would not be itself cooled off and solidified in the process, and thus fail to reach the surface. Hence, we conclude that certainly the greater part of the water, or its constituents and perhaps almost all of it, which comes from volcanoes was originally contained in some form in the magma and brought up by it from great depths. In contrast to the resident surface water of the earth this is known as *magmatic*, or sometimes less happily as *juvenile*, water. It appears probable that the other volatile constituents previously mentioned, page 192, are in great part, if not entirely, likewise original.

Cause of Ascension. — What causes the magmas to ascend we do not know, but the fact that the situation of the great volcanic chains is on those belts along which movement and disturbance of the lithosphere * has taken place is a significant one. For these are, apparently, zones of weakness in the lithosphere, and have thus afforded favorable positions for the upward movement of the magma, and its escape to the surface. As will be explained more clearly later, the lithosphere is divided into great blocks, or segments, and these have in times past moved up, or down, with respect to one another. It is often noticeable that where one of these great blocks, measuring hundreds or thousands of square miles in area, has sunk, this has been attended with uprise of magma, outflows of lava, and commonly volcanic action. Instances are found in the depressed tracts which form the great Rift Valley of East Africa, the valley of the Rhine, the region of the Christiania fiord in South Norway, and the sunken sandstone area of Connecticut and Massachusetts.

All this suggests that the upward movement of the magma is due in some way to variations of pressure induced by changes of position of the segments into which the lithosphere is divided, although we do not know just how to explain its mode of operation. Some hold that the gradual contraction of the solid earth through gravity, aided by other processes, causes the magmas to rise. The old idea that the earth has a hot, liquid interior, and that the downward pressure of the contracting cold and solid lithosphere forces this liquid out and thus gives rise to volcanoes, has been completely disproved by a number of considerations, and is no longer held. The independent eruptions of adjacent volcanoes in the same group, and the fact that the lava column in Mauna Loa stands 10,000 feet higher than that in Kilauea, only 20 miles away, are disproofs of this view, while others will be mentioned later.

As to the *seat* of volcanic action, or the point from which the magma may be considered to move on its upward way, we know nothing. One plausible conjecture we can make is this. From the study of earthquakes, as we shall see later, it appears that the earth consists of an inward portion with specific gravity about 5.6

* The earth's outer shell of rock.

covered by a shell whose specific gravity is about 2.7, and this shell is thought to be not much thicker than a small number of miles, and to change gradually into the denser core. The specific gravity of much of the lavas erupted by volcanoes is not much over 3.0, while that of a large portion is considerably less. Hence it would appear that the material forming the lavas was probably not derived from far within the inner core and this may determine the seat of action as being not many miles deep.

Hot Springs and Fumaroles

Introductory. — In the foregoing description of volcanoes it has been shown what an active role gases and vapors, especially water vapor, play in their eruptions. But long after a volcano has ceased to be active and has passed into a dormant, or dying, stage these volatile substances continue to issue from its crater, or from its flanks, or even from places in the surrounding country. In the same way thick beds of extruded lavas continue, often for years, to exhale steam and other vapors. And, as we shall show later, it has often happened that large and small bodies of magma have penetrated into the outer shell of the earth, without attaining the surface or forming volcanoes, and these in solidifying, like the lavas, have given off quantities of these same volatile substances which work upward through fissures and pores in the rocks. The class of phenomena produced by such emanations at the surface it is now proposed to describe. They may appear as vapors, or in liquid condition; the former may be considered under the general heading of *fumaroles*, the latter under *hot-springs*.

Fumaroles. — This word, which is derived from a Latin verb, meaning to smoke, is applied to those instances where steam and other heated vapors escape with more or less force from fissures, or holes, in the rocks and soils. While steam is the most common substance, other vapors, such as hydrochloric acid, hydrogen sulphide, carbonic acid, etc., also occur. When the fumaroles give off sulphurous vapors they are often termed *solfataras*, from the Italian word for sulphur. It is noticeable that in the hottest fumaroles the acid gases are prominent, in those less hot various other volatile compounds, often hydrogen sulphide which decomposing gives rise to deposits of sulphur, while as the fumaroles become cooler, or cold, carbon dioxide becomes the chief emanation. Although different regions vary in the proportion and nature of the products exhaled, this general rule seems to hold, not only in time but in space, so that whether one considers the decline of activity at a given center,

or travels away from an active one the change from hot acid vapors to cooler carbonic acid exhalation is noticed. A view of several fumaroles is seen in Fig. 174.

The Solfatara near Naples had its last eruption in 1198; since then it has been in the condition of discharging steam mingled with sulphur vapor, and this has given rise to the use of the term *solfataric stage* when volcanoes become quiescent, or are dying. Some of the great cones of the Northwest, like Mt. Shasta, appear to be in a dying solfataric stage. In the Yellowstone Park the solfataric condition is still active and fumaroles abound in many places. While at times and in places the steam given off in fumaroles can be ascribed to magmatic origin, it is often increased, or even surpassed, or replaced, by descending surface water

Fig. 174. — General view of the Norris Geyser Basin, showing hot-springs and fumaroles, and the white siliceous deposit of geyserite from them. Yellowstone Park.

being vaporized, either by contact with hot rocks, or by the heated volcanic exhalations. This is probably the case in the Yellowstone Park.

The closing condition in which carbon dioxide gas is given off is found in numerous places where volcanic activity still abounds, and in many where vulcanism has long since died out. It may happen that it issues directly from the ground as a gas spring, and such occurrences are known as *mofets*. Being heavier than air it may collect in still weather in depressions near the vent, and, since it is colorless, tasteless and odorless, such pools of the gas may prove deadly traps for animal life, by suffocating such creatures as may enter it. This is illustrated in "Death Gulch" in the Yellowstone Park and in similar places elsewhere. But the gas is far more likely to encounter ground-water on its upward way and thus give rise to carbonated springs, which passing through limestone may deposit carbonate of lime. See page 155. Some hold that the carbon dioxide is derived from the decomposition of the limestone, $CaO{\cdot}CO_2$ and this may, in some places, and in part, be true, but in other places it can with good reason be referred to a magmatic origin.

Hot-springs. — In volcanic regions hot-springs are likely to occur. We may attribute their origin to different causes; they may be due to descending surface waters being heated by coming in contact with hot rock masses below, or by hot magmatic vapors passing into them, and their returning in this heated condition to the surface. When they occur in active or quiescent volcanic regions, as in the Yellowstone Park, they are probably due to a varying combination of the causes mentioned above. Warm springs also occur in regions where no direct evidence of connection with volcanic activity can be shown; in this case they are probably deep, or fissure springs (see page 147), and the water has been warmed by contact with rocks whose temperature has been raised by mechanical means, such as crushing, or by chemical changes going on within them.

It is impossible in certain regions, to tell in the case of hot-springs and fumaroles how much of the water (and steam) is surface and how much is magmatic in origin. It probably varies in different cases. Hot-springs in the rainless arid interior of Australia have been regarded as mostly of magmatic origin. The proof that magmatic emanations have passed into such waters is found in the presence in them of such substances as sulphur, arsenic, boric acid, etc., in quantities and under conditions which show that they could not have leached out from the original rocks of the country. In the Yellowstone Park it is probable that the greater part of the water is of surface origin which becomes heated by contact with lavas still hot and returns in this condition, but there are good indications that magmatic vapors, once very active, still play a subordinate part.

While there are various types of hot-springs, dependent on their temperature, substances in solution, etc., the most interesting are boiling springs and geysers. Warm carbonated springs depositing travertine have been already described, page 156.

Boiling Springs. — Actively boiling springs are a feature of many volcanic regions. A considerable number of them occur in the Yellowstone Park, especially in the different geyser basins, see Fig. 175. They exhibit various gradations from pools which are hot, but rarely boil, or else quietly simmer, into types which boil strongly and steadily and some even more or less violently and with somewhat explosive energy, interrupted by short periods of repose. The latter form transitions to the geysers mentioned beyond. So long as the supply of water is sufficient to enable the spring to have an overflow it remains limpid, and it usually has a deep blue, or green color, but if the evaporation through boiling is equal to the inflow the water is more or less turbid from particles of disintegrated rock, and eventually becomes a mass of boiling mud. The mud may be white, or variously tinted yellow, red, purplish, or black by oxides of iron and manganese, and such hot-springs are called "paint-pots,"

"mud-pots," etc. The mud as it increases in amount may become so thick and viscid as to prevent regular ebullition and, owing to

Fig. 175. — "The Devil's Punch-Bowl." A hot-spring boiling in the cup-like deposit of geyserite it has formed. The opening is several feet in diameter. Upper Basin, Yellowstone Park. W. H. Weed, U. S. Geol. Surv.

Fig. 176. — Mud Volcano, Waiotapu Valley, New Zealand.

the accumulating steam pressure, action may happen spasmodically and with some violence, the mud being thrown into the air and about the vent, where it collects in considerable masses, see Fig. 176.

These are known as *mud volcanoes*, or mud geysers. They usually mark a declining stage of activity in the life of a hot spring.

Geysers. — This term, from an Icelandic word meaning to gush, is applied to certain hot springs which at intervals spout a column of hot water and steam into the air. Depending on the size of the geyser and its special peculiarities the column of water may be only a few feet high, or from that up to several hundreds; the eruption may last a few minutes, or several hours; the quantity of water discharged may be small, or be many thousands of gallons; the jet may play steadily and continuously straight up, or be fitful, be composed of minor jets, or be thrown in inclined directions. The

Fig. 177. — Basin of the Oblong Geyser, partly empty but filling with water after an eruption. The rounded masses are deposits of white silica, geyserite. Yellowstone Park. Haynes photo.

interval between eruptions may be a definite one of a number of minutes, or hours, or it may be quite irregular, and several days may elapse between them. Each geyser has in these ways its own peculiarities. As they are special kinds of boiling springs they are not common and, so far as known, appear to be confined to three regions, the Yellowstone Park, Iceland and New Zealand.

Some geysers consist, at the surface, of a basin which may be several feet to a number of yards long and broad and rather deep. The sides and edges of the basins are usually beautifully ornamented by the deposits of silica described beyond, and terminated at the bottom in tubes or fissures leading to the heated depths below; this type is illustrated in Fig. 177. The tubes and basins are, except

after eruptions, filled with water at or near the boiling point. In other types the geysers, by their deposits have built up mounds or cones of silica, from a foot or

Fig. 178. — Lone Star Geyser in eruption, showing cone of geyserite. Yellowstone Park. Haynes photo.

two to several yards high which form upward continuations of the pipes. See Fig. 178. Of the Yellowstone geysers the most celebrated perhaps is the one

Fig. 179. — Old Faithful Geyser in action. The jet of water is 100 feet high, at this time. Yellowstone Park.

known as "Old Faithful" which for many years after its discovery had a very regular interval between eruptions of about 65 minutes, Fig. 179. It is now be-

coming more irregular. This, and the decline of activity in other geysers, or springs, does not mean any immediate diminution of thermal action in this region, only changes going on in the underground system of pipes and fissures which conduct and supply the hot water. Altogether there are several dozen fine geysers in the park, while the number of hot-springs, fumaroles and thermal vents of various kinds amounts to several thousand. It is a fact not easily explained that geysers have been found only in felsite lavas.

Cause of Geyser Action. — The intermittent eruptive action of geysers depends on the relation between pressure and the boiling point of water, as was pointed out by Bunsen in connection with the great geyser in Iceland. The boiling point of water under the ordinary pressure of the atmosphere at sea-level is 212° F.; increase of pressure raises it, a decrease lowers it. Thus the boiling point at the bottom of a column of water will be raised by the pressure of the superincumbent layer above it; as shown in Fig. 180, it will gradually rise as we follow the tube from the surface downward. If, however, the cavity, or fissure, be large and open the heated water below will rise, convection currents will be established mingling the water, so that it will have nearly, though not quite, the same temperature in different parts of the cavity, and a regular boiling spring will result. But if the tube be long, narrow, tortuous, or constricted, convection will be prevented, or restrained, and the water must boil in different levels at different temperatures corresponding to the pressures. Suppose at a point 230° in the figure the boiling point is reached, bubbles of steam are formed, the column of water above is raised a little by the expansion, the bubbles of steam rise into the cooler liquid above and collapse, the column of water settles back with jarring, thudding sounds commonly heard before eruption. The temperature of the water will gradually rise until it is just about at the boiling point for each level corresponding to its depth and pressure. Finally when a sufficient volume of steam is formed in the lower parts, the expansion will cause some of the water in the basin, or cone, at the top to overflow, this lowers the pressure throughout the tube, and the water at each level, being now heated above the boiling point for the

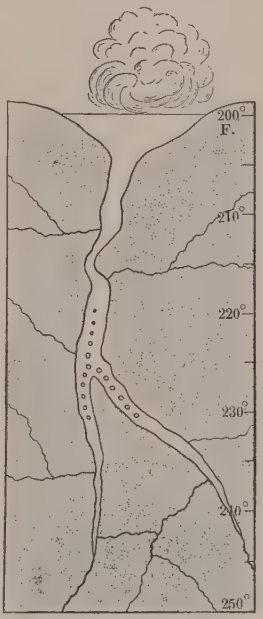


Fig. 180. — Diagram to illustrate conditions necessary for geyser action.

diminished pressure, will immediately flash into steam, and a mingled column of steam and hot water will be driven roaring out of the pipe into the air. After the eruption is over the system fills again by inflow of ground water through the fissured rock, and the process is repeated.

The varied forms of fissures, underground conduits, and water supply account for the peculiarities shown by different geysers. It has been found that adding alkaline substances, such as soap or lye, to the waters of geysers causes some of them to erupt very quickly; this makes the water somewhat viscous and the liberation of steam difficult and rather explosive, leading to sudden lowering of pressure and eruption.

That the source of heat for the geysers and hot-springs in the Yellowstone Park must be quite deeply seated is shown by their occurrence in, and on the shores of, Yellowstone Lake, an immense body of very cold water, below which the rocks must be cooled to considerable depths.

Hot-spring Deposits. — It has been previously shown that where warm springs, especially if they contain carbon dioxide in notable quantity, come up through limestone beds they form deposits of calcareous tufa or travertine. See page 157. But the waters of actively boiling springs and geysers, which occur only in regions of recent geological activity, are mostly alkaline and carry *silica*, SiO_2, in solution, which they deposit as a whitish material, varying from compact to spongy in texture, and known as *geyserite* or, more commonly, *siliceous sinter*. This forms the geyser cones, or is deposited in incrustations, often of great beauty, in and about the margins of the hot-spring and geyser basins. The solutions are dilute and the rate of deposition is very slow when it occurs only through drying, but is hastened by the action of organisms. Formations of rather considerable size and thickness have been, and are being, made in this way, as seen forming the floor of the basin in Fig. 174. While hot-springs and geysers are not geological factors which are of importance from the magnitude of the results which they achieve, they are yet of great significance in a proper understanding of certain processes, such for instance, as the deposit of certain ores of metals, and are of wide popular interest.

It has been found by Weed that, as in the case of travertine, page 156, the deposit of silica is very largely due to the secretion of it by certain low forms of vegetable life, diatoms and *algæ*, the latter related to sea-weeds, which flourish in the warm and even hot waters. The beauty of many of the pools is greatly enhanced by the rich coloring which these growths add to them. It may be that they represent to us some of the earliest and most primitive types of life which existed on the earth.

Besides silica the hot-springs may form other substances; the waters in some places are acid and deposit sulphur and alum salts. In other cases sulphides of arsenic and of metals are found, throwing light on the formation of ore bodies.

CHAPTER IX

MOVEMENTS OF THE EARTH'S OUTER SHELL; EARTHQUAKES.

Introductory. — Experience and observation show that the outer shell of the earth is not fixed and rigid, but undergoes changes which result in movement of one part of it as compared with another. The evidence is overwhelming that this has occurred repeatedly in the past, and in all of those places that it is permitted us to examine the structure of the earth's crust. The movements of the different parts of the outer shell have been differential with respect to one another, and not only up and down, but back and forth in directions tangential to the earth's circumference. The evidence that such movements have taken place lies in the results which they have achieved, and these we shall see and study in detail under the heading of Structural Geology in a later part of this work. Here it is intended to show that gradual and massive movements of the crust of the globe have taken place, not only in the remote but in the immediate past, with results of magnitude, and that they are still continuing. We shall first examine the evidence and then see what conclusions may be drawn from it.

Datum Plane. — It is evident that in order to consider the rate and extent of movement of different areas of the earth's surface, or even to know that it has occurred, we must have some fixed point of reference. For vertical movements the level of the sea immediately suggests itself as a datum plane to which they can be referred. For, if it can be shown that relative displacements of land and sea levels have occurred in any place, it is natural to think that the movement must be that of the land, since the sea, averaging the tides, must maintain a mean tidal level throughout its whole extent. Along coast-lines, therefore, we use the sea surface as the point of reference for vertical movements of the earth's outer shell.

The idea of the fixedness of the sea surface must not, however, be carried too far. As explained on a previous page (82), the ocean does not present us a truly geometric surface, but a warped one. And, as further explained under coral islands, page 177, the sea-level has varied within recent geologic times, first, by the withdrawal of a part of its water, due to its accumulating as ice on the land, and second, by the restoration of this water to the ocean basins by melting of most of the ice. And also there are reasons for thinking that the

ocean has increased in size and depth through geologic time by the constant addition of magmatic waters, as explained under volcanoes. It is also more than probable, that, as from time to time the earth shrinks recurrently, with sinking and warping of the floors of the ocean basins and corresponding possible increase of velocity of rotation, such changes will cause movements of the ocean waters on its surface. Such shiftings are registered by apparent up and down movements of the shores giving rise to the strand-lines mentioned below. But, since such changes in the ocean are very gradual and general, while the movements of the land we are considering are local, much more rapid, and much greater in degree, we may still for our purposes measure them against the sea-level as a relatively fixed point.

Elevation. — The most striking proofs that upheaval of the land from the sea has occurred consist in the elevation of those features which we definitely associate with the sea, or its edge, so that they are now inland and high above it. Thus in various parts of the world

Fig. 181. — Ancient sea-caves in former sea-cliff at back of elevated beach, showing strand-line. Coast of Fifeshire, Scotland. Geol. Surv. of Scotland.

outcrops of rocks with dead marine organisms, such as barnacles, or other shells, and corals, still attached to them are found high above sea-level, or the rocks are pierced by the tunnels of rock-boring shell-fish (*Lithodomus*) which may still contain their shells. This shows that such changes have recently occurred, while the presence of the remains of shells and other marine organisms as fossils in the rocks of the highest mountain ranges proves that they have also happened in the remote past.

Another line of evidence consists in the elevation of those conspicuous features which the edge of the sea makes in its geologic work of eroding the land and which were described in previous pages 89–93. Thus raised beaches, wave-cut and wave-built terraces, forming level benches of country terminated inland by sea-cut cliffs, the latter often pierced by wave-formed caves, show the elevation of a former sea-margin, Fig. 181. They are often spoken of as a *strand-line* and commonly show as a more or less distinct

Fig. 182. — Elevated strand-lines cut in sandstones and limestones. Straits of Belle-Isle, Labrador. Schuchert photo.

topographic line, or level, more or less parallel to the present shore line and above it.

Still another line of evidence, of a positive character, is found in what may be termed human records. Thus in southern Sweden the uprise has been under observation for a long period and has been measured by marks placed on the shore. In one place the elevation was about two feet in a century, but the rate is not everywhere uniform and it varies also from time to time. All the facts point to the Scandinavian peninsula as having gently swelled up for a long period, so that its crest in the northern part of Norway is 1,000 feet higher than it once was. Raised strand-lines are a noticeable feature in many northern regions, Fig. 182. Similar facts have been recorded in other parts of the world. Thus the raised strand-lines prove that within a recent geological period the west coast of South America has been elevated in places over a thousand feet, and the process is probably still going on.

Depression. — The evidence that the land, in places, has subsided below sea-level is less striking than that of elevation, but not less convincing when fully understood. We must here look for a different kind of evidence, for the fact that the sea has encroached upon the land is not in itself a proof of subsidence, since this may be due to simple landward erosion, as previously explained, page 92. Rather we must seek for the submergence of features which are definitely characteristic of land-surfaces. Such are found, for example, in submerged forests, and in buildings or other structures of mankind, now standing in the water. Increasing depth of average water-level over well known rocks or reefs in harbors is another proof.

Submerged forests are found at various places along the Atlantic coast-line from Maine southward. The diagram, Fig. 183, shows the stumps still standing

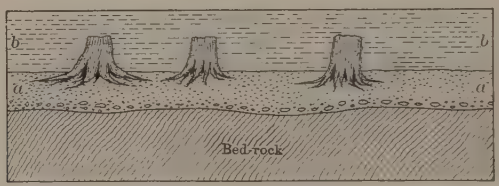


Fig. 183. — Diagram showing submerged forest. *a*, old forest soil with stumps standing in it; *b*, marine deposits of silts and sands.

in the forest soil, while above are the marine deposits covering them up. It is clear that this could occur only in situations sheltered from the waves of the encroaching sea, which would otherwise have swept away the forest-soil, as in protected nooks and corners of estuaries. Sometimes the tree stumps are yet uncovered and may be seen standing up on the sea-bottom in the water. Submerged peat-bogs which have become tidal flats are rather common and tell the same story. Borings in the deltas of great rivers, such as the Mississippi and the Ganges, as described beyond, show the subsidence may continue for long periods. All the collected evidence goes to show that the Atlantic sea coast from Maine southward has gradually sunk within the last geologic period; whether it is still sinking is more doubtful though the facts at hand rather tend to show that it is doing so.

Drowned Valleys; Fiords. — The most impressive evidence of subsidence of the land, when its significance is understood and appreciated, is seen in the irregular coast-lines produced by the drowning of valleys with production of bays and estuaries, or of canyons with the making of fiords. This has in part already been discussed, page 94, and Fig. 53. The seaward extension across the submerged continental shelf for long distances of river channels, such as the Hudson, points also in the same direction, for manifestly these great

trenches, sunk in the sea-floor, could not have been cut while the area was covered with water, but only by river or glacial action, or both, when it stood at a higher level and was a land surface.

Subsidence and Deposit of Sediment. — It is a commonly observed fact that in many parts of the world where heavy deposits of sediment are being laid down by rivers in the sea adjacent to the coast subsidence of the ocean bottom is in progress. This is noted in the deltas of large rivers, like that of the Mississippi. Borings through them show a great depth of deposits, sometimes these are marine, sometimes fresh-water in nature, as shown by the shells which they contain, alternating with beds of peat and buried forest-growths. These facts show that subsidence has been going on for a long period, and not at an even rate, but as an interrupted process, whose variations permitted land, fresh-water, and marine deposits to be formed. Not only is this occurring in the present but, as we shall see later on, it has happened in many places in the past so that enormous thicknesses of deposits, up to 40,000 feet or even more, have been laid down in particular localities, which have been afterwards raised and exposed to observation. Such great thicknesses of sediments are associated with mountains, as we shall see later, for elsewhere they are much thinner. Since the products of land waste are chiefly deposited close to the shore, see page 97, and as we cannot imagine a depth of 40,000 feet at the edge of the land we are forced to believe that subsidence must have been occurring along with the deposition, to permit accumulations of such thickness of the sediments.

It has been a view of some geologists that the subsidence is caused by the load of accumulated sediment. They consider the earth's crust to be in such a state of equilibrium, *isostatic balance*, so-called, maintained by the yielding of plastic material below, or the rocks being forced under pressure to act as if plastic, that where the crust is lightened by erosion it will rise, and where it is loaded by sediment it will sink. But it is to be noted that should elevation occur in one area of the crust and subsidence take place in an adjacent one, erosion would tend to cut down the rising area and fill up the subsiding one. The mere fact that shifting of material occurs is not in itself a proof that it is the cause of the change of levels; it may be the effect of such change rather than the cause. Probably it is both cause and effect. The subject will be considered more fully in another place.

Evidences of Elevation or Depression Inland. — We can hardly assume that movements of the shell involving changes of level are confined to the sea-coasts; they must also occur inland, in the interior of the continents. That this has happened during the past is plainly shown by several lines of evidence: for example, by the

bodily sinking of tracts of land, such as occurred at New Madrid, Missouri, in 1811–1812 and by the behavior of antecedent rivers in maintaining their courses through upwarps and thus forming canyons as previously discussed, page 69. But there are also other facts that prove changes of level have taken place very recently inland and are probably still going on. This is shown by the tilting of lakes, as illustrated in the diagram, Fig. 184.

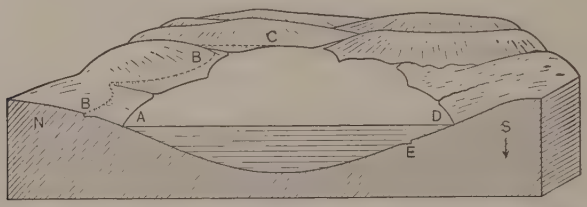


Fig. 184. — Showing tilting of lake basin. *AD*, present lake level. *BB*, raised shore line disappearing under lake at *C*. Land has been depressed to south (*S*) and on this side the former shore line, *E*, has been drowned.

The Great Lakes present one of the best examples of this. To the north-east of them the land appears to be rising in a huge low dome or shield at a rate which has been estimated at several inches in a hundred miles per century. Since they lie on the southwest side of this rising area they are being tilted to the west and south. On the north-east side the old strand-lines are several hundred feet above the present water level and slope toward it as they are followed west and south. Since the lakes discharge to the east the raising of their outlets has caused them to enlarge, expanding them to the west and south. The rise of water at Chicago is estimated to be about 9 inches a century and it is thought that, if this continues, in 3000 years the lakes will drain through that place to the Mississippi, since it will then be the lowest point in the rim.

Warping movements downward may also be shown by the conversion of a part of a river valley into a lake. Thus downwarping has converted a portion of the upper course of the Ottawa River into a long narrow body of water, known as Lake Temiskaming. It occupies the site of a warped canyon and is very deep and narrow.

Another line of evidence, which so far has not been very much studied, or well established, consists in gradual changes in scenery, brought about by slow warping effects of the earth's crust, like the appearance of a distant object, such as a building, rock, or hilltop, over the crest of an intervening ridge from some well determined spot, whence in previous years it could not be seen. A number of such changes are reported, and some of them may be due to earth movement, but since they must take place very slowly, and the work of erosion must also be taken into account, until proper photographic and surveying records have been long established, not much dependence can be placed upon them.

Classification of Movements. — In a geologic sense the shell of the earth is never quiet or at rest; but is always undergoing slow motion; in one place apparently motionless for a period but in

another slowly rising, in another gradually subsiding. During one epoch the continents are heaving upward and the seas retreat from their borders, at another they are sinking and the oceans advance and eat their way inland. At times these motions have become more energetic and certain belts of the earth's shell have been crushed together, both longitudinally and transversely, with folding and fracturing and the rising up of mountain ranges, as we shall see more in detail in a later place. All such movements of the outer shell whether of continental masses, or in mountain making, whether of folding or fracturing, or dislocation of one part with respect to another part, whether upward or downward, or by horizontal thrusting or stretching, are comprehended under the general term of *diastrophism*, and the forces producing such results are spoken of as *diastrophic*. For the sake of convenience also when diastrophic forces affect and move the continental masses they are termed *epeirogenic*, from the Greek *epeiros*, a continent; when concerned in making mountain ranges, *orogenic*, Greek *oros*, mountain and *gen*, producing.

These diastrophic movements are probably all to be referred to the same general cause, but it is useful to distinguish between different phases according to the results achieved. Thus, in addition to the terms epeirogenic and orogenic gradual warping movements of the land surfaces, such as those taking place about the Great Lakes, have been called *bradyseisms* (from the Greek, *bradus* and *seismos*, meaning slow earthquake).

Intermediate between the epeirogenic forces concerned in the making and moving of continents and ocean basins and the orogenic ones giving rise to mountain ranges are those which elevate or depress great blocks of the outer shell. The movement is essentially in a vertical direction. The upward movement of such areas on the continents has given rise to plateaus, such as those of the Colorado and of Thibet, while the downward one has yielded depressed tracts, like the great Rift Valley of East Africa with its contained lakes. In the ocean basins the submarine plateaus and the 'deeps' (see page 83) point to similar movements and results. The areas thus raised or depressed do not move as units, but are broken into great blocks whose movement is attended with more or less dislocation, the result of which we shall have occasion to consider later. All the movements which tend to produce changes in the earth's surface are often spoken of as *deforming*, and the results achieved by them as *deformations*.

Cause of Diastrophism. — When we endeavor to account for the various movements which the earth's outer shell has undergone, and is still undergoing, it appears that we can find for them an *immedi-*

ate cause but not at present an *ultimate* one. Concerning the immediate cause there is quite general agreement of opinion, and it is held to be due to the *unequal contraction* or shrinking of the earth, taken as a whole. There is a great body of proof which shows that the outer shell of the earth has undergone this contraction and that it is probably continuing; through this the surface is gently warped up or down and at times there has been more energetic crushing in certain belts and areas. The proof of this we shall study in detail in a later part of this work.

But concerning the ultimate cause, the reason why the earth should contract, why it should do so in an irregular manner, and how the shrinkage causes diastrophism, there are, indeed, many opinions but, as yet, unfortunately not much real knowledge; what is known and the most important views that are held will be discussed in a later place; before taking them up we will next consider certain results of these movements which are not only of interest and importance in themselves, but, as it has recently appeared, have taught us some valuable facts regarding the character of the earth's interior and seem destined to teach more as their study continues. We refer to earthquakes, whose consideration follows in the next section.

In the preceding discussion of diastrophism reference has been made in a number of places to upward and downward movements. These should be understood to be relative terms, the position of one area with respect to its surroundings. For it is possible that in the shrinkage of the earth each of the areas and our datum plane, the ocean level, are all moving towards its central point, but that some move faster, or more, than others and thus cause these relative

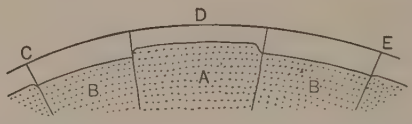


Fig. 185. — Diagram of deforming movements. *A* and *B*, *B* have sunk from the original surface *C D E*, but *B*, *B* more than *A*, so that the latter appear to have risen. *A* is a horst, *B*, *B* are graben.

changes. See Fig. 185. Those areas which stand at a higher level, or apparently rise, are often spoken of as *positive* elements of the shell, in contrast to which the depressed tracts are termed *negative* ones, terms whose significance will appear when we study the geography of the world in past geologic times. Areas, like *A* in the diagram, Fig. 185, are known as *horsts*, those like *B*, *B* *graben*, from the German, the one meaning an elevation, the other a trench, or trough.

The main positive elements of the earth's crust are, or have been, continental areas, the negative ones are the deep ocean basins. The continental areas are

again broken into smaller tracts which are subordinate negative and positive elements according to their motion with respect to one another; it is these that are commonly distinguished as horsts or graben.

Earthquakes

Introductory. — In the preceding section it has been shown that in a geological sense the earth's shell is undergoing constant movement on a large and massive scale. In what we may term a present sense it is constantly subjected to relatively small and often rapid motions. These may arise from a great variety of causes, and, ordinarily, they are not perceived by us, though they may be detected by suitable instruments. When they occur as tremors which we can distinctly recognize they are called *earthquakes*. These are not only interesting in themselves as geological phenomena, but are of such great importance to humanity, on account of the loss of life and great destruction which they frequently entail, that they have been made the subject of wide-spread and continued investigation. As a result there is perhaps no field of geological inquiry in which greater progress has been made, especially in recent years, and some of the more important facts and conclusions are here presented. The study of earthquakes is known as the science of *seismology*, from the Greek, *seismos*, an earthquake.

Cause of Earthquakes. — An earthquake is a trembling, or undulatory motion, in the more or less elastic rock-shell of the earth, communicated to it by an impulse or shock of some kind, as a bowl of jelly might be set in vibration by a smart tap on the side of the containing vessel. The shock or impulse is evidently the cause of the earthquake, and the question arises, what is the origin of such shocks? The evidence shows that they may arise from several causes, most of which must be considered of minor importance compared with one major source, which appears to give rise to all great earthquakes.

One minor cause is found in violent volcanic outbursts, like that of Krakatoa in 1883 and of Bandaisan in Japan in 1888, but earthquakes produced in this way are light in intensity and quite limited in extent. Moreover, many outbursts are not attended by any shocks, or but extremely feeble ones, like that of Mont Pelée in 1902. It used to be thought that volcanic action was an important source of earthquakes and this idea is frequently revived; but the careful comparison of the two phenomena, especially in Japan, has shown that there is no necessary connection in occurrence between heavy earthquakes and volcanic eruptions.

Another minor cause may be found in the sudden caving in of subterranean cavities, due to the yielding of the roof to the weight of superincumbent rock masses. This is most liable to happen in limestone regions, since this rock is

apt to be removed in solution by underground waters, as previously explained page 152. It is possible, as has been suggested, that the earthquakes, which in 1811 devastated the lower Mississippi valley, especially about New Madrid in southern Missouri, were partly due to this cause, though the area affected is too extensive and the effects of the earthquake shocks produced were felt to too great distances for it to have been more than a minor one.

It has now been rather definitely settled that the main cause of earthquakes, especially the heavier ones, is the jar given the earth's shell by the sudden forming of a fracture in its outer portion, or, perhaps, a sudden slipping, or displacement, along the walls of an already existent fracture. The upper part of the earth's shell is divided by fissures into blocks, both great and small; such fractures probably die out below at a depth of twelve miles, or thereabouts, where the overlying weight exceeds the crushing strength of the

Fig. 186. — Map of a part of California, showing the position and extent of the fault-line, A–A, movement along which produced the earthquake of April 18, 1906.

rocks, though temporarily, at the time of formation they may penetrate more deeply. Above this the blocks may adjust themselves to the contraction of the earth as a whole by settling down, and by movement along the walls of the fissures. Fractures along which dislocation has taken place are called *faults* and, as we shall see later, such faults are a matter of great importance in structural geology. The scale on which such phenomena take place is very great; the fault along which abrupt movement caused the great earthquake in California on April 18, 1906, has been traced, with

only two or three interruptions, a distance of 600 miles and displacement occurred along, at least, 250 miles of it. See Figs. 186, and 187. This is, however, exceptional and distances of 40–50 miles

Fig. 187. — Trace of the fault fissure concerned in the California earthquake of 1906. G. K. Gilbert, U. S. Geol. Surv.

are more common. The fissures, if already existent, are not necessarily open, their walls are pressed tightly together, and perhaps in places healed by deposited material, and sudden forced motion, even of only a few inches, with friction and perhaps rupture, where the masses involved are so tremendous, is quite sufficient to generate a shock which would produce a disastrous earthquake. The motion is commonly vertical, and may amount to several feet and even yards, see Figs. 187, 188 and also Fig. 277, but lateral and oblique movement is also liable to occur; thus the horizontal displacement on the sides of the fault line in the California earthquake of April, 1906, was from 8 to 20 feet, as shown by the separated ends of fences, etc., see Fig. 189, while the maximum vertical dislocation was not more than from one to three feet.

The most recent view of the cause of earthquakes, according to Reid,* is not that the shock is caused by the bodily slipping movement of a great block of the earth's shell in mass, but rather by the sudden fracture of the rock along a line in an area which has long been under gradually accumulating strain. He states the causes and effects as follows.

The fracture of the rock, which causes a tectonic earthquake, is the result of

Fig. 188. — Displacement, or fault, along a great fissure which produced a heavy earthquake in Japan in 1891, at Midori in the Neo Valley. K. Ogawa, photo.

elastic strains, greater than the strength of the rock can withstand, produced by the relative displacement of neighboring portions of the earth's crust.

These relative displacements are not produced suddenly at the time of the fracture, but attain their maximum amounts gradually during a more or less long period of time.

The only mass movements that occur at the time of the earthquake are the sudden elastic rebounds of the sides of the fracture towards positions of no elastic strain; and these movements extend to distances of only a few miles from the fracture.

The earthquake vibrations originate in the surface of fracture; the surface from which they start has at first a very small area, which may quickly become very large, but at a rate not greater than the velocity of compressional elastic waves in the rock.

Effect of Shock. — The student must carefully bear in mind the difference between cause and effect in earthquake phenomena; thus in Fig. 188 the displacement shown is not the result of an

* Elastic-Rebound Theory of Earthquakes; H. F. Reid, Bull. Dept. Geol. Univ. Calif., Vol. 6, No. 19.

earthquake, but the cause of one. The effect of the sudden movement along a fault line, or the forming of a new one, is that vibrations are sent outward in the earth from that place, and these are the earthquake, as it is perceived at a distance. Within a certain

Fig. 189. — Horizontal displacement, or shove, without appreciable vertical change, as shown by the separated parts of the fence. One is looking perpendicularly toward the plane of the fissure. California earthquake of 1906. G. K. Gilbert, U. S. Geol. Surv.

zone, on either side of the fault line, or on both sides, the destructive effects observed in the demolition of buildings, etc., may be chiefly due to the sudden shift in the ground, especially if this takes place horizontally; at increasing distances from this line the vibrations are more and more the cause of the different things which may happen. Thus the earthquake is propagated as a series of waves in the earth, as in an elastic body. When these emerge at the surface the ground is thrown into very short, rapid vibrations, which even in severe earthquakes have a range of only a few inches. The waves

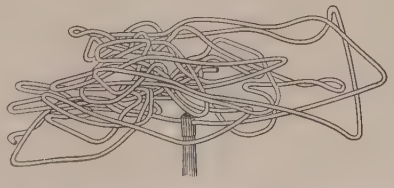


Fig. 190. — Wire model showing path traveled by a particle of matter during an earthquake; after Sekiya.

along the surface move at a rate of about two miles per second. The motion is not only back and forth, but also up and down, and the path described by an individual particle may be very complicated, as illustrated in Fig. 190. The nature of the elastic waves transmitted through the earth and what they have taught us will be discussed in another paragraph.

It used to be thought that earthquakes were generated from a point at some depth, say from two to six miles, below the surface and this was called the *focal point*, or centrum. The point immediately over this on the surface was called the *epicenter*. This latter point was determined by drawing concentric closed curves, called coseismal lines, on a map of the region through points of simultaneous arrival of the waves, as indicated by observatories, clocks, etc. See Fig. 191. By other mathematical methods the distance below the epicenter of the focal point was calculated. These methods led to discordant results for a given earthquake, and eventually to the discovery that there might be several epicenters situated in a line, or that where earthquakes habitually occurred in a given region the epicenters were situated on this line. Further investigation showed that these were fault lines and this led to the present understanding of their cause, as previously stated. Thus the former ideas of a focal point, of its depth below the surface, etc., have in large measure lost their significance.

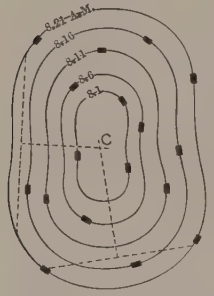


Fig. 191. — Map of coseismic lines.

Recent Examples. — On August 31, 1886, the city of Charleston in South Carolina was visited by a severe earthquake which killed and wounded a number of people and did great damage to buildings and other structures. The shock was distinctly felt as far away as Chicago, a distance of 800 miles. It has been suggested that this was caused by the sudden slipping seaward of vast masses of sediment accumulated on a descending coast-line, but the attendant phenomena leave little doubt that like most other earthquakes it was due to the settling and adjustment of shell blocks.

On May 3, 1887, a tremendous earthquake occurred in the province of Sonora in northern Mexico. It was felt over the greater part of New Mexico and Arizona, but as these were then very thinly settled regions little damage was done. The fault occurred at the base of a mountain range which was uplifted in places twenty feet.

In 1899, a great earthquake took place in southern Alaska. As the region is mostly uninhabited it passed almost without notice at the time. Studies which have since been made show that considerable alterations in topography took place at the time of its occurrence, especially about Yakutat Bay. Marked changes were also induced in the great glaciers of this region (page 128) by the shattering of the ice and by snow slides from the mountains. See Fig. 277.

On April 18, 1906, occurred the great earthquake in central California which has been previously mentioned. The loss of life, from various causes may have reached 1,000; many towns and cities were greatly damaged; but the chief destruction took place in San Francisco. The city, damaged by the shock, was in

great part destroyed by a resulting conflagration, which could not be checked because the pipes carrying the water supply were laid across the fault line, and the displacement cut them in two.

Fig. 192. — Destruction caused by earthquake vibrations, Stanford University, Cal. April, 1906. W. C. Mendenhall, U. S. Geol. Surv.

In August, 1906, the coast of Chile was visited by a severe earthquake, which did great damage in Valparaiso and other places. The number of persons killed was estimated at several thousand. After-shocks continued for a long time while readjustment along the fault surface was going on. The west coast of South America is noted for its earthquakes, in connection with which notable elevation of the coast line has occurred.

On January 14, 1907, a heavy earthquake happened at Kingston, Jamaica, with destruction of property and changes in the coast line and in the harbor, due to faulting.

The greatest disaster of modern times occurred on Dec. 28, 1908, when Messina and Reggio, cities on the narrow strait which separates Sicily from the mainland of Italy, were completely destroyed by a terrific shock. It is estimated that possibly 200,000 lives were lost in this frightful catastrophe. The region has repeatedly suffered from this cause in previous times; it is one in which crustal readjustment is constantly going on.

These are only a few examples out of many that might be selected. Scarcely a day passes that shocks are not recorded from some part of the world by the earthquake observatories.

Seismic Belts. — Observation shows that while earthquakes occur in all parts of the world they are most likely to happen in

Fig. 193. — Map of seismic belts in the Eastern Hemisphere. On S. L. Penfield's stereographic projection.

certain well-defined tracts, which lie in what we may call the great seismic belts. These surround the earth as zones roughly in the direction of great circles which cross at an angle of nearly 70 degrees.

One belt follows the western coast of North and South America, the Aleutian Islands and the island groups along the eastern coast of Asia and thus defines the Pacific Ocean. The other includes the Mediterranean, the Alps, the Caucausus, the Himalayas and so on into the East Indies. These are shown on the accompanying maps in Figs. 193 and 194. It will be noticed that in a general way they coincide with the great volcanic belts previously described, page 204, and thus tend to show that there is a common cause for both sets of phenomena. It is also a notable fact that where these belts lie along the continental coasts, as in North and South America and on the eastern coast of Japan, the land descends very sharply, with-

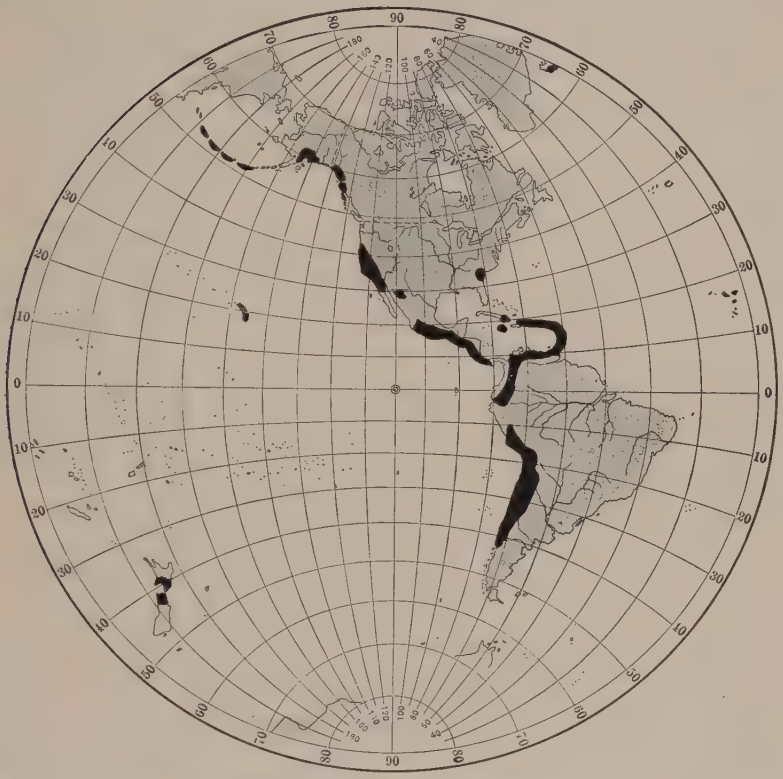


Fig. 194. — Map of seismic belts in the Western Hemisphere. On S. L. Penfield's stereographic projection.

out any broad intervening shelf, to the depth of the ocean. See page 83. These slopes are the edges of concave tracts of the ocean floor, from 100 to 300 miles wide, which border the continents and which appear to be sinking; while conversely the bordering land areas appear to be rising, and in long stretches have been elevated as mountain chains, as we shall see later. These are the belts or zones of weakness in the earth's crust where the stresses and strains incidental to the contraction of the earth are being constantly relieved by movements, and in which, therefore, earthquakes are continually recurring.

It is often thought that certain regions are practically exempt from danger of earthquakes because no real disaster has happened in them since they have been settled and cities have sprung up. Yet in New England, for example, in the 230 years following its settlement over 230 distinct earthquakes have been recorded, an average of one a year, though probably none have been of the first

magnitude. Where the shocks are frequently recurrent and slight, the danger of a large movement and heavy shock seems less; where quiet has long reigned in a seismic belt, the shock which eventually comes is apt to be severe, suggesting that the strain in the one case is constantly eased, in the other cumulative. It has also been noticed that a heavy shock in one seismic belt seems to be followed, not long after, by one in a very distant belt, rather than by one in neighboring regions, as if, locally, the stresses and strains were eased. This is illustrated by the Valparaiso earthquake which followed soon after the San Francisco one in 1906.

Submarine Earthquakes; Tsunamis. — What is stated in the foregoing discussion of seismic belts suggests that a large part, possibly the greater part, of earthquakes take place on the ocean bottom, on the descending sides of the deeps. That they do occur beneath the sea is shown in several ways, such as the shocks communicated to vessels on the surface above and the rupturing of submarine cables. And with the sensitive instruments by which, as will be shown later, it is now possible to record distant earthquakes and

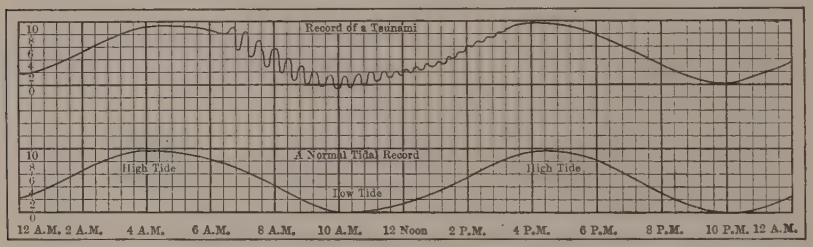

Record of a Tsunami
A Normal Tidal Record
High Tide
Low Tide
High Tide
12 A.M. 2 A.M. 4 A.M. 6 A.M. 8 A.M. 10 A.M. 12 Noon 2 P.M. 4 P.M. 6 P.M. 8 P.M. 10 P.M. 12 A.M.

Fig. 195. — Record of tsunami by tidal gauge. Vertical lines represent time spacing on the paper, driven horizontally by clockwork. Horizontal lines show height in feet as recorded by the rising and falling pencil of the gauge.

determine their place of occurrence many are found to happen beneath the sea. The most important thing which these submarine earthquakes cause is the huge wave which they may generate in the sea. Such waves have long been known under the title of tidal waves, a misleading name since they have no connection with the tide; they are now generally called *tsunamis*, from their Japanese name, by seismologists. They may be of immense size, from 100 to 200 miles from crest to crest, and at the point of origin 40 feet high. They are so broad that in the open sea, unlike wind waves (see page 88) they would not be perceived; but if, on approaching the coast, they are still of considerable height they may pile up in huge breakers and, sweeping far inland, cause enormous damage and loss of life.

Lisbon in 1755, Japan in 1854 and in 1896, Peru in 1868, suffered well-known instances of great and disastrous tsunamis, the number of victims in some cases

being 20,000. These vast waves are felt over whole oceans and move with tremendous speed, from 300 to 500 miles per hour. Those from Japan have crossed the Pacific in nearly 12 hours, and are registered by tidal gauges. At such distances their height may be only a few inches; but the ebb and flow of from 15 to 30 minutes, like small subordinate tides on the top of the regular tide, would be registered as wavy lines by the instrument. See Fig. 195. It is these records which enable us to determine the size of the wave since they give the time of oscillation; the speed between distant points being known, the size = velocity × time of oscillation.

It has been supposed that these waves were due to the uplifting or depressing of an area of the sea bottom by the shock, but Reid has recently shown that it is much more probable that they are caused by the elastic rebound of the crust which follows when it has been gradually strained to such an extent that a line of fracture finally and suddenly occurs, with quick movement on either side of the break, as in the California earthquake of 1906.

Recording Earthquakes; Seismographs. — Very delicate instruments have been invented, called seismographs, which record the tremors due to distant earthquakes, and the study of these records has led to important geological conclusions. The principle upon which such instruments are now constructed is simple; if a heavy mass of metal be suspended like a pendulum, owing to its inertia it will remain for a long time at rest when the shock arrives, while the earth vibrates beneath it. A point or pencil of some kind is secured to the suspended weight, while under it, on a bed-plate rigidly attached to the earth, is a paper or other medium suitably prepared to record the motions of the point which lightly touches it. If the earth oscillates beneath the suspended pencil a series of lines will be drawn on the vibrating paper. If the paper, instead of being made fast, be a strip continuously carried along by clockwork the pencil when at rest will draw a straight line upon it; when vibrations of the earth occur the line will be broken and will oscillate sinuously from one side to the other. See Fig. 197. Such a record is known as a seismogram.

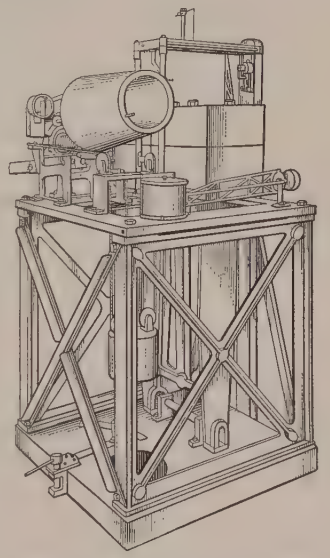


Fig. 196. — Seismograph with astatic pendulum, Wiechert's model.

While in principle, a modern seismograph is simple, in construction it is a rather complicated instrument (see Fig. 196) since it is arranged to record not

only horizontal motion in two directions, East-West and North-South, but also the vertical motion as well. It is from such records in three directions that the wire models shown on page 233 are constructed. Since the intervals of time are marked on the moving paper the instrument records the time of arrival of the shock and also the duration. The directions of diversion of the markers from their regular paths show also the direction from which the shock has come.

Seismograms. — The study of seismograms of distant earthquakes has led to the discovery that the main shock is preceded by smaller quick vibrations which are recorded when the seat of disturbance is greater than 1,000 kilometers (about 620 miles) from the recording station. These are known as the preliminary tremors.

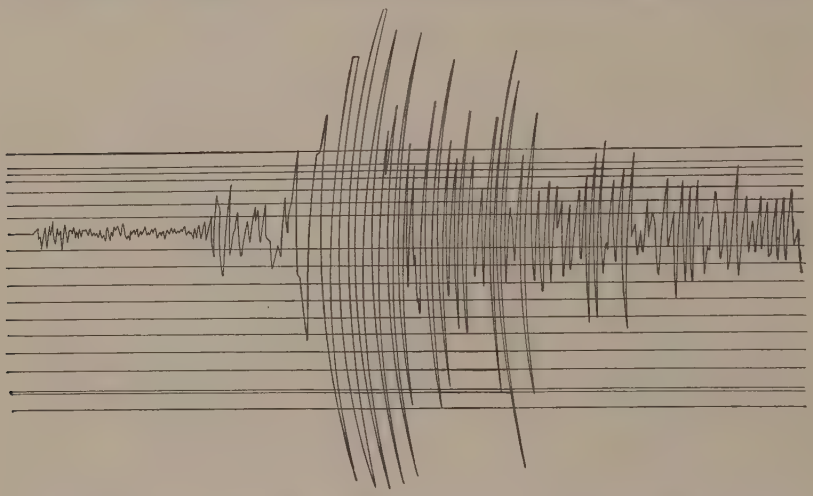


Fig. 197. — Record of the earthquake in Messina on Dec. 28, 1908, as shown by a seismograph, in Göttingen, Germany, over 1,000 miles distant.

Thus a normal seismogram has the characters seen in Fig. 198. From a number of considerations it is now agreed that these preliminary tremors represent the shock which has come by the quickest path *through the earth*, that is in the general direction of a chord from the seat of disturbance to the recording station, while the large waves (see Fig. 198) represent those that have traveled by a longer route over the surface circumference. The time between the arrival of the preliminary tremors and that of the main shock is proportional to the distance of the place of disturbance, and the following rule has been worked out which gives roughly the distance from the seat of shock; the duration of the *first* preliminary tremors in minutes (and fractions of minutes), less one, is the distance of the place of disturbance in thousands of kilometers, (1,000 kilometers = 621 miles approximately).

It is now generally agreed that the first preliminary tremors, coming through the earth, are longitudinal waves of compression, the direction of vibration of a point being in that of the line of propagation, that is to and fro, while in the second preliminary tremors coming through the earth the wave is one of distortion, with the directions of vibration transverse. in a plane normal to the path traveled. On the surface these waves are 'rocking' ones.

The large surface waves passing around the world in the direction opposite to that between the points of the seat of shock and the recording station, and thus through their antipodes, have also been detected by the seismograph.

If the distances from three recording stations are known, then by drawing

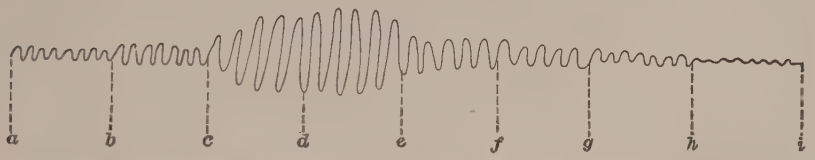


Fig. 198. — Seismogram of distant earthquake, *ab*, first preliminary tremors; *bc*, second preliminary tremors; *ce*, main shock; *fh*, later phases; *hi*, tail (after Omori).

circles on the globe with these distances as radii and the stations as centers, the place of disturbance may be determined by the intersection of the three circles. In this way the place of shock has been located in some instances on the ocean floor.

Geological Deductions from Seismograms. — The fact that the preliminary tremors, which are supposed to travel through the earth, arrive at distant points so long a time ahead of the main shock cannot be explained alone by the shorter path traveled. The time interval shows that they are also propagated at a much greater rate of speed than the vibrations traveling in the outer shell of the earth. The deduction from this is that they move in a denser, more elastic medium which enables them to gain speed as they go. Moreover, the concordant results in different directions show that inside of the outermost layer, which we know is heterogeneous in composition, the earth is homogeneous, or regularly arranged around its center in structure or, if non-homogeneous, the heterogeneous parts are relatively so small and numerous that different paths of considerable length through them give the effect of uniformity. Moreover, the average velocity increases with the distance of the recording station, thus the rate of transmission along

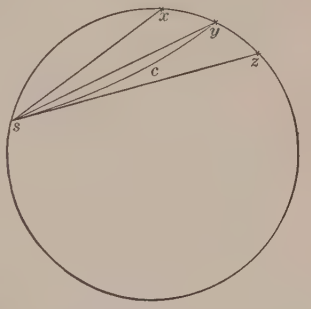


Fig. 199. — Paths of transmission of earthquake shock through the earth. *S*, seat of shock; *x*, *y*, *z*, recording stations.

sz, Fig. 199, is greater than along *sy*, which in turn is greater than along *sx*. Reid has calculated from the data afforded by the California earthquake that, at the depths below the surface given, the velocity of the first preliminary tremors is as seen below:

Depth below surface, miles	Speed in miles per second
0	4.5
272	6.0
612	6.9
1,225	7.8
1,968	7.9

These results show not only that velocity increases with the depth, but more and more slowly as the depth increases, and this would seem to indicate that the density and elasticity of the earth increases with the depth down to a certain region. Seismographs of sufficient accuracy and delicacy have not yet been so generally installed that data concerning earthquakes at distances as great, or greater, than one-third of the earth's circumference are sufficiently reliable for us to draw very definite conclusions from them. The chord connecting the ends of the arc of one-third the earth's circumference (120°) cuts the earth's radius at its middle point, and thus it is this outer shell, 2,000 miles thick, concerning whose density and elasticity the seismographs have so far given us the most information.

From the fact that the rate of speed increases with the depth, in the outer shell, 2,000 miles thick, it follows that the quickest path of wave transmission from the seat of shock to a distant station in this portion of the globe will not be a straight line, as from *s* to *y* in Fig. 199, along the chord of the arc, but will be a curved line concave upward, somewhat as the line *scy*. In other words, by following this line the waves gain more in time in entering more elastic layers than they lose in distance, hence seismologists generally assume that the path followed by the waves making the first preliminary tremors at a distant recording station is a curved one. This is of some importance because, assuming the path to be a straight one and noting the fact that the preliminary tremors do not generally show in seismograms unless the distance is greater than 1,000 kilometers, the deduction has been drawn that there must be a sharp boundary between the outer rocky heterogeneous shell of the earth and the inner homogeneous core, and that, since the chord of an arc of 1,000 kilometers at its middle point is 12 1/2 miles below

the surface, this must be the thickness of the outer layer. Others assuming a curved path have made the thickness as much as 800 miles. But Reid has shown that the probable reason why the preliminary tremors do not show in the records of 'near' earthquakes is that instruments are not generally sufficiently delicate to record and distinguish them as distinct from the principal shock, until distance produces time intervals great enough to be recognized.

We have not yet knowledge enough of the earth's interior, nor are the data yielded by the seismographs from earthquake shocks, though promising, sufficiently accurate and comprehensive for us to fix the limits of the outer shell of the earth, if, indeed, there can be said to be a very definite one. This subject will be further considered in a later chapter.

Geological Effects of Earthquakes. — There are several geological effects from earthquakes, but they are, comparatively speaking, of minor importance. The earth is often ruptured by the passage of the wave with the formation of fissures, which may be of some depth. A more important one is the starting of landslides and avalanches in mountainous regions, through the jarring of the earth. A variation in the flow of water from springs, or the forming of new ones, has also been observed.

Much more important are the movements of the shell blocks which cause earthquakes, but as previously remarked, these are the cause and not the effect of the shocks; these movements have been considered and the results which they produce are treated under Structural Geology.

DIVISION II. STRUCTURAL GEOLOGY

CHAPTER X

GENERAL STRUCTURE AND PROPERTIES OF THE EARTH

In the foregoing pages there has been given a general description of the various *processes* which have been, and still are, modifying the outer portion of the earth, the part which is directly open to investigation and study. In considering these agencies we have, to some extent, been led to notice *the material* which they operate upon, and *the results which they have achieved*, but this has been done only in so far as was necessary to understand the principles involved, and therefore, only in a superficial way. It is now appropriate that these materials and results should be more fully treated, and we shall commence by considering the earth as a whole, in relation to its general structure, and the properties it is known to possess, and in stating briefly the ideas which are held regarding the nature of its interior.

The Earth and Its Neighbors. — The earth is one of a group of planets which revolve around a common central orb — the Sun. Some of these, like Jupiter, are much larger than the earth, some like the asteroids, or minor planets, are much smaller; some are much nearer the sun, others farther away. The group has very nearly a common plane of revolution about the sun, as suggested in Fig. 200, and this fact is held to have an important bearing on the origin of the system. The path of the earth about the sun is not a circle, but an ellipse, one of whose foci is the sun; the deviation of the ellipse from a circle is relatively small; the average distance of the earth from the sun is nearly 93 millions of miles, it is about $1\frac{1}{2}$ millions of miles nearer, or farther, from the sun according to its place in its elliptical path. The eccentricity of the ellipse varies during long periods of time, from 100,000 to 200,000 years, and at a maximum the earth may be over 13,000,000 of miles nearer the sun in summer than in winter.

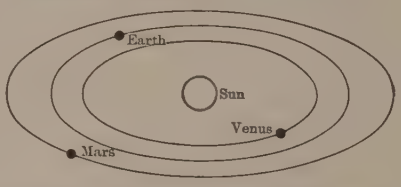


Fig. 200. — Planets revolve about the sun in nearly one plane as suggested by three of them.

As we shall see later, this has been held by some to be a cause sufficient to produce great climatic changes and glacial epochs. Besides revolving about the sun, the earth, as is well known, is spinning on its own polar axis, each revolution in 24 hours giving rise to day and night. This axis is not perpendicular to the plane of the earth's orbit, but inclined to it at an angle of about $23\frac{1}{2}°$, and this gives rise to the seasons, summer and winter, alternately in each hemisphere.

The earth is a very insignificant fraction of the universe as the latter is known to us, and for that matter so is the solar system itself. Nevertheless, throughout the vast extent of the universe, with its myriads of suns and solar systems in various stages of development, the same general physical laws, which we know upon the earth, appear to govern. Gravity operates in the same manner; light is transmitted everywhere by the same kind of vibrations; the spectroscope tells us that the same chemical elements are found in distant suns and meteors as on our earth. Nor do the meteorites which we gather in our journey through space, and which appear like the disrupted fragments of former worlds, bring to us substances strange to the earth. There appears, consequently, to be a unity of law and a uniformity of material throughout space, and we consequently feel justified in assuming that facts and reasoning derived by astronomical study of the other heavenly bodies may be logically applied in our study of the earth.

Form of the Earth. — The earth is not a true sphere but a spheroid, flattened at the poles, and the polar axis, or diameter, on which it revolves, is about 26 miles less than an equatorial one. This oblateness, or bulging at the equator, is the form naturally assumed by a revolving mass, which, like a liquid, is free to assume its shape in response to the forces acting upon it; a mass of liquid in space, free from outside forces, would become a sphere through the power of its own gravitative attraction; if revolved it would bulge at the equator and flatten at the poles, and the amount of distortion would depend on the speed of rotation. It is held that the degree of distortion of the earth stands in direct relation to its mass and rate of rotation.

It is argued by some that this is a proof that the earth was once in a liquid condition, but this is not a necessary conclusion. For if the forces tending to distort the earth were greater than the rigidity it possesses, the earth would yield to them, no matter whether it were liquid, or solid throughout. Moreover, the ideas of liquid and solid, and the notions of rigidity which we attach to them, when referred to the vast bulk of the earth, and the enormous forces of several kinds which govern its condition, have relatively little meaning.

It has been suggested that the rate of rotation has been gradually lessening, or in other words the day has been growing longer, during geologic time. The reason advanced for this is that the tides, sweeping across the oceans in a direction opposite to that of rotation, on being checked by striking against the continents, act as a brake which tends to retard the rapidity of revolution. If this be

admitted, and also the view that the form of the earth is in relation to the rate of rotation as mentioned above, it would follow that its surface area has been decreasing throughout geologic time. For, if the speed of rotation should lessen, the amount of oblateness would also decrease, and the earth approach a more spherical shape. But since the sphere is that form in which a given mass of matter has the smallest surface area the latter would also decrease. But in regard to this view it has recently been demonstrated by Chamberlin and others, after careful computations, that the amount of retarding effect of the tides on the earth's rotation is so small that it must be considered as a negligible factor. The geologic evidence is also decidedly against the view that during geologic time there has been any definite change in the form of the earth through decrease in its oblateness! The evidence will be considered later under mountain ranges.

Others hold, however, that the earth has been contracting, and, since a contracting body tends to revolve faster, this should counteract any retarding effect of the tide. This effect when studied geologically also seems negligible, in that the amount of shrinkage during the period recorded by geological events has been too small to cause such a change in the rate of rotation as should affect the form of the earth.

Density and Rigidity of the Earth. — The density, or specific gravity of the earth, as determined in several ways is about 5.6. The density of the outer shell is about 2.7 and this indicates that the interior must be different in constitution from the outer part. If the outer shell is relatively thin the density of the inner core need not be very different from that of the earth as a whole. If, on the other hand, the outer portion of the earth be considered rather thick, a considerable fraction of the earth's radius, then the density of the interior must be proportionately higher. The indications given by the study of distant earthquakes seem to favor the view that there is no definite crust and that the density increases gradually with the depth.

The *rigidity* of the earth, or its capacity for resisting deformation, and its *elasticity*, by virtue of which it tends to resume its original shape when deformed are relatively high, as much as one and a half times that of hard steel, and perhaps more.

The rigidity of the earth is shown by its capacity to resist the deforming tendency produced by the attractive forces of the sun and moon. We see the effect of these on the watery envelope of the earth in the production of tides, and the fact that the earth retains its shape in spite of them, is the strongest proof we have that its interior is not in a liquid condition, in the sense in which we use that term on its surface, as was once firmly believed. For, if the earth, or any considerable portion of it, were a liquid covered by a relatively thin shell, we should have interior tides and consequent displacements of the outer crust, which is not the case. Thus, whatever may be the condition of its interior, it possesses that degree of rigidity which we associate with solid bodies.

Its highly elastic nature is shown by the speed and uniformity with which it transmits the compressional waves of earthquake shock in any direction through

its mass. Compared with the vast size of the globe these shocks are relatively very feeble, and that they should be transmitted such great distances through it is a striking testimonial to the elastic nature of its interior. That the earth transmits distortional waves of earthquake shock, as explained under earthquakes, is also a proof that its interior is not liquid, or, at least, that it possesses the physical quality of elasticity we associate with a solid and not with a liquid.

It has been suggested that the greater elasticity of the interior of the earth is due to increasing density caused by the tremendous pressure of the superincumbent material. It is calculated that the pressure at the center is equal to 3,000,000 atmospheres or 45,000,000 lbs. per square inch, and, of course, it varies with the depth; at the surface it is one atmosphere, at $\frac{1}{5}$ the radius, or about 800 miles down, it is over 500,000 atmospheres, or 7,500,000 lbs. per square inch. We can scarcely conceive that such pressures would not cause an increase in density, especially towards the center, and the transmission of earthquake shocks, as mentioned above, indicates that the difference in density and elasticity is gradual and perhaps due to increasing pressure alone, but it may also depend on a difference in the kind of material forming the inner and outer portions.

From the high specific gravity of the earth and its magnetic properties it is thought by some that the interior consists largely of iron, and the fact that most of the material, which comes to us from space in the form of meteors, is composed of this metal is held to strengthen this view.

Interior Heat of the Earth. — This subject has been mentioned under volcanoes and may be now further discussed. The interior heat manifests itself directly in two evident ways, by the uprise and outflow of molten magma and heated vapors, and by the increase of temperature as one descends into the earth. Indirectly its presence is also indicated by certain changes and phenomena, to be discussed later, which have occurred in the rock-shell of the earth and for which the presence of heat has been necessary.

The rise of temperature as one penetrates the rock-shell varies in different regions. The average is stated as 1° F. for every 60 feet, but this means little from the practical point of view, for the increment may be much greater or less than this. In the region of the copper mines of Michigan, which are nearly 5,000 feet deep, it is about 1° F. for every 100 feet, while in mines in other places it may be almost five times as rapid.

In the relatively shallow depths reached by mines it may be much influenced by local conditions, thus in some the rapid increment noted may be due to chemical processes, such as the oxidation of ores containing sulphur, while the slow rise of temperature noted above in the Michigan copper mines may be partly induced by the greater conductivity of the rocks of that area. Also these rocks are very old ones geologically, and it has been noted that in old rocks the rise is slow, perhaps 100 feet or more to 1° F. while in young volcanic rocks it may be comparatively rapid, 28 feet to 1° F. In Great Britain it is stated to vary from 34–130 feet. It is often a matter of great importance in mining and tunnelling operations: thus some mines have been found difficult and expensive to work owing to the

great heat encountered, and it is thought that on this account mining below certain depths would not be feasible. In the making of the great railway tunnels which traverse the Alps this factor has been a serious one; the surfaces made by connecting points of equal heat increment as one goes down, and known as *isogeotherms*, are not necessarily parallel to the general surface of the earth, but more or less irregular and rise in the interior of mountain chains, so that in a horizontal tunnel one encounters greater heat as the tunnel proceeds inward. See Fig. 201. Thus, although the economy of operation on lower grades would more than offset the cost of driving longer tunnels at lower levels, the interior heat prohibits their construction below certain levels, and in one recently constructed it was so great there was fear for a time that the undertaking would have to be abandoned.

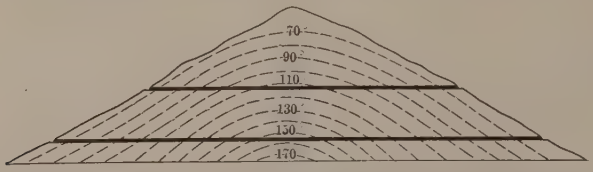


Fig. 201. — Illustrating the rise of heat in the interior of mountains and the difference in the difficulty of constructing high and low level tunnels.

If the heat increased regularly 1° F. for every 60 feet of descent there would result a temperature of 3,600° F. at 41 miles; this would liquefy rocks at the surface, especially if the melt contains water vapor, and it is probably as high a temperature as that of the hottest lavas, which attain the surface, or higher. As shown by volcanic phenomena we can safely assume that at all events there are regions within the earth where the temperature attains a height of at least 3,600° F., = about 2,000° C., but beyond this all is unknown and a matter of speculation. The depth of 41 miles is also an assumption, for it is based on the rate of 1° F. for 60 feet; while the average rate, after some depth is attained, may be quite different.

If one assumes that the rate of heat increase mentioned above were uniform to the center of the earth the temperature would there be about 350,000° F., but for several reasons this seems highly improbable. The outermost shell of the earth is a poor conductor of heat, the inner portions with higher density should be good conductors; if we should imagine that at some depth below the surface it is relatively hot, say 2,000° C., the fall off in heat, or rate of decrease, in the outer part towards the surface would be rapid; while in the other direction from this point toward the interior we should expect the rise in temperature, with increasing density and better conduction, to be relatively slow.

Nature of the Earth's Interior: Origin of Heat. — Our ideas of the cause of the interior heat of the earth must of necessity be closely connected with those regarding the nature of its interior, and this in turn leads to speculation concerning the origin of the earth itself. The last subject is historical in character and is, therefore, properly

treated in the second portion of this work. In their bearing on the question of the interior structure of the globe and its heat some prominent views which have been advanced are, however, of importance and may be briefly considered.

a. Nebular hypothesis. The view which has been long, and is still widely held, is that the earth, formed as the condensation of a portion of a vast glowing cloud of extended vapor, was once a molten mass whose outer shell through cooling solidified as a solid crust, while the interior, though excessively hot, also solidified through the enormous pressure of the superincumbent layers; and that between the two, is either a zone of liquid because the pressure there is not sufficient to solidify it, or of material solidified by pressure but so hot that if in any way the pressure is sufficiently diminished it will liquefy. According to this view the heat of the earth is primitive; what it now exhibits is that remaining from its former condition. It may be remarked in regard to this hypothesis that the supposition of a liquid layer is no longer tenable in view of what has been learned concerning the rigidity and elasticity of the earth as previously shown; if the general hypothesis with the second alternative be accepted, the zone where liquefaction will ensue, if pressure be sufficiently relieved, becomes of geologic importance and will be further considered elsewhere.

A modification of the above hypothesis consists in the assumption that the increase of heat is so great that towards the center matter cannot remain in either the solid or liquid condition, but, being heated above the critical point, it must be in the gaseous form and, on account of the enormous pressure, contracted to a density far beyond that of solids at the surface. By reason of this condensation the substances are supposed, although in the gaseous condition, to possess so great an internal viscosity, or resistance to flowage, that the mass has a rigidity sufficient to meet the demands which it has been shown above astronomical considerations impose. It is inferred that certain facts concerning the transmission of earthquake shocks favor this view. It is to be noted that, if the core increases so greatly in density, the outer shell of low specific gravity must be of considerable thickness in order that the average density of the whole earth may be maintained at the proper figure of 5.6 and this appears to agree with the results of seismic investigation, previously stated. Under the conditions and with the properties assumed, the term "gaseous" seems hardly applicable. With the enormous pressures reigning at the center of the earth the condition of matter must be very different from anything known at the surface, whether it be moderately, or enormously hot. Under sufficient pressure and proper conditions the rigidity of solid metals at the surface of the earth breaks down, and they undergo through mashing a flowage like liquids. But the resistance to flowage is greater than would be the rigidity at the earth's surface. Under such pressures it would seem as if substances would be resolved into a condition neither solid, liquid, nor gaseous, as we know them, and which might be, indeed, a fourth state of matter; the condition they might assume on relief of pressure may depend on the temperature.

b. Planetesimal hypothesis. In recent years serious objections have been advanced which throw doubts upon the validity of the nebular hypothesis in the form previously stated and another has been propounded in the endeavor to meet them. The statement of this is found in the second part of this book; it is sufficient to say here that the earth is regarded as having been built up gradually by the infall and accretion of relatively small solid bodies termed "planetesimals."

Through the enormous pressures exerted under the influence of gravity contraction has ensued, and gaseous matters have been expelled, giving rise to the atmosphere and surface waters. The contraction is thought to be the source of the interior heat; in the interior core, where the contraction is greatest, the most heat develops, and this flows outwardly to an intermediate zone. The latter is held to receive heat faster from the interior than it loses it by conduction to the outer crustal zone; as a result melting ensues, and the liquid material, by the forces to which it is subjected, works its way upward to the surface and, along with the escaping gases, gives rise to volcanic phenomena. The escape of heat through volcanic agencies regulates the temperature of the intermediate zone, and prevents any notable mass of it, beyond relatively thin volcanic threads, from becoming liquid. This hypothesis has been recently advanced; it apparently meets the objections raised against the former one; whether it will encounter new difficulties of its own time alone can tell.

c. The *radio-active* properties of matter have still more recently been appealed to as a source of the earth's interior heat, as has been previously mentioned under the causes of volcanic energy.

We have learned that in the disintegration, or breaking down of certain elements, such as uranium and thorium, into other elements, such as radium and lead, and in the further disintegration of radium into helium and by-products, relatively enormous quantities of heat are developed. Furthermore, radio-activity is found to be a widely spread property of rocks, especially of the igneous ones. That a part of the earth's interior heat is due to this cause is unquestionable; recent investigations would seem to indicate that it may be entirely so. It also seems most probable that radium, and the heat which it produces by its disintegration, are confined to a shallow zone of the exterior, but a few miles in depth. It is stated that investigation in the Alpine tunnels has shown that the rate of heat-increase is proportional to the radio-activity of the rocks. While we are not yet in a position to see clearly the full significance of the matter it seems probable that this conception, of the part played by radio-activity, may lead, as it is further investigated, to ideas concerning the physical state of the earth's interior, and the cause of its different energies, which are quite different from anything expressed in the foregoing discussion.

Isostasy. — This term (from the Greek, meaning equal standing) is applied to a theory of the physical condition of the globe in which it is conceived to be in such a state of relative plasticity, either through the viscous yielding of material, or the forced flow of solid matter, such as rocks, through gravitational pressures, that from circumference to center each column of substance composing it, like the spokes of a wheel, is in a sort of hydrostatic equilibrium with every other column. That is, columns of equal diameter have the same weight. But as some parts, like the continents, stand at a higher level than other parts, like the deep ocean basins, they must do so because the material composing them, in the top part of their column, is deficient in density compared with the other parts below them in level. See Fig. 185. As the outer shell of the earth is composed of heterogeneous substances, and through erosion and

other processes constant shifting of material is going on, the theoretical condition supposed above is not perfect, and the earth is constantly tending to bring itself into isostatic equilibrium by the slow flowage of material below, through the stresses produced by gravity. According to this view the continental masses are the result of a kind of relative floatation of lighter material below their surfaces and, therefore, project, while the ocean basins are depressed because of the denser material below them.

Aside from the general geologic evidence that those areas, where lightening of the crust by erosion is taking place, are rising ones, while those parts of the sea-floor where rivers are laying down heavy deposits are sinking (see page 225) this theory receives some additional support from the results of surveys made by the U. S. Government to determine the form and curvature of the United States and from pendulum experiments to ascertain in different regions the force of gravity. These show that there is a general isotatic balance between the continents and ocean basins, but that the large mountain ranges are probably not in isotatic equilibrium.

It has been calculated that at a depth of about 70 to 100 miles isostatic compensation is complete and that the adjustments take place in this upper shallow zone. The variation in density between the highest large area on the continent, the Colorado Plateau (reaching to 11,000 feet) and the greatest ocean depth of the Atlantic (18,000 feet) which have been investigated, is actually small, only about 3 per cent less, or greater than the normal one at sea-level and less than the difference between different kinds of rocks. This seems in agreement with the general observation that the rocks composing the continental masses are of lighter specific gravity than the basaltic ones which the mid-oceanic volcanoes usually contain, and which latter are our clue as to the nature of the material underlying the ocean floors. It should be said, however, that, while the experimental work mentioned shows that some sort of compensation is probable, the exact results which it was thought to yield have been considered to be very doubtful. Further work in this direction is needed before we shall be able to consider the geologic evidence fully supported by the mathematical results obtained by physical measurements.

It may at first thought seem contradictory to what has previously been stated concerning the rigidity of the earth that it should yield to the comparatively small loadings and unloadings that isostatic equilibrium would imply, or, in other words, that it is so plastic and so weak a structure. But the student must remember that all such terms are relative and that the earth, while adjusting itself to minor differences of load and level, may yet be sufficiently strong to resist the stresses which astronomical considerations show the sun and moon impose upon it.

The theory of isostasy may prove of importance in enabling us to understand certain geological processes, but, as it has not yet been sufficiently investigated to receive general acceptance and certain facts which appear opposed to it have not yet been explained, it should be regarded at present as tentative.

Relief Form of the Earth

General Features. — The irregularities of the earth's surface, or its relief, divide naturally into major and minor groups. The former

are the continental masses and ocean basins, while the minor groups consist of mountains as opposed to interior valleys and basins on the land, and of islands as contrasted with the deeps on the sea-floor. The mean height of all the lands above sea-level is about 2,400 feet, of North America about 2,000 feet; the average depth of the sea about 13,000 feet. The highest elevation of the land, Mt. Everest in the Himalayas, is 29,000 feet; the lowest known point in the ocean, in the Pacific, is 31,000 feet deep. This makes the greatest difference in relief 60,000 feet or nearly 12 miles. Relative to the size of the globe its relief is extremely small and it is, therefore, comparatively smooth; see Fig. 202 which shows its greatest roughness. The features of the land are divided into *plains*, such as the Atlantic coastal plain, *plateaus*, such as that of the Colorado, and *mountains*, like the Appalachians extending from Canada to Georgia and Alabama. In regard to the grouping of the relief forms of the

Fig. 202. — Mt. Everest in comparison to the size of the globe. Part of the arc of a globe with radius of one foot is shown; on this Mt. Everest, *E*, would be about $\frac{1}{50}$ of an inch high. *D*, in a similar way, shows the greatest depth of the ocean.

earth certain facts are of interest and importance. The continents have a tendency to consist of interior basins with mountain chains as coastal rims, while the ocean basins reverse this with deeps near the continents and submarine ridges, or up-swells of the bottom, in mid-ocean. And in a number of cases the highest and most important ranges on the edge of a continent border the greatest deeps in the ocean floor, as for instance the Andes in South America and the partly submerged mountain chain which forms the Japanese islands, and is the real eastern border of the continent of Asia; close to these the ocean floor descends to great depths. See page 236. This is not meant to imply, however, that mountains are found only at the continental edges, for they may extend in a wide zone far into the interior, as in western North America, or form systems crossing a continental mass, as in Asia.

Character of North America. — North America is the most typical of the continents in that it is bordered by mountainous tracts on either side and contains the great basin of the Mississippi and its tributaries in the interior. The following broad features of the continent, and especially of the United States, the student will do well to bear in mind, as they enter into many of the discussions of its geology. On the east and south the land rises from the sea

as the Atlantic coastal plain and this meets the base of a rugged mountainous tract of country, which stretches from Alabama to Canada and is known as the Appalachian mountain system. This gives way to the interior basin whose higher eastern and western parts form the Allegheny and Great Plains plateaus. The lower part of the basin is the Mississippi plain. To the west the Great Plains give way to the long series of north and south ranges which form the western back-bone of the continent and are grouped under the name of the Rocky Mountain Cordillera. Between this and the Pacific ranges, which make the western rim of the continent and

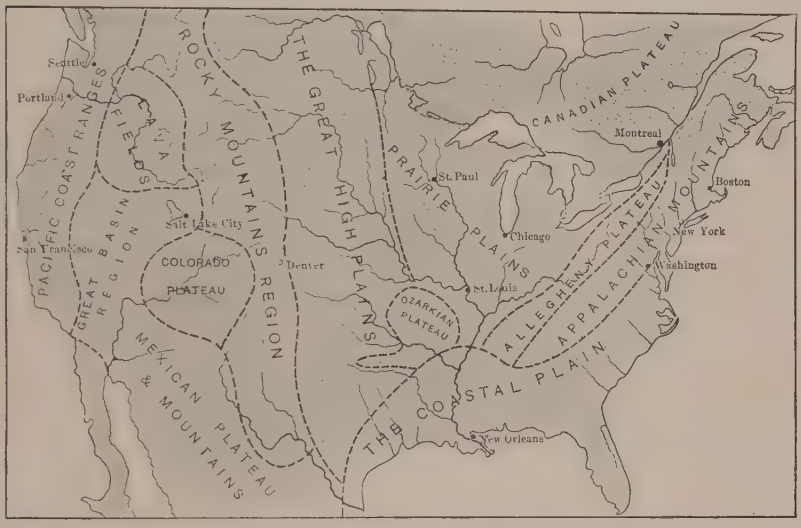


Fig. 203. — Map showing chief physiographic divisions of the United States and part of Canada. The boundaries are approximate and must not be considered as very definite.

consist chiefly of the Coast Range and the Sierra Nevada, lies the Great Basin. These relations and other minor ones are seen on the map, Fig. 203.

The Outer Zone of the Earth; Rocks

As has been shown in the preceding discussions we know but little regarding the interior of the earth; chiefly it is the outer zone of rock of which we have extensive and positive information; upon it we live and exert our activities; we penetrate into it for fuels of various kinds, for metals, water, building material, and other things, and for reasons upon which the physical side of modern civilization depends. A thorough knowledge, therefore, of the component parts of this shell and its structure is of the highest im-

portance. The component parts are rocks, and we shall begin our inquiry by a study of the different kinds of rocks and the varied modes in which they occur. For the most part, as we shall see, the causes which have produced them have been described in the foregoing part of this work; we are here concerned with the results.

Definition and Classification of Rocks. — The word rock, geologically speaking, means the material composing one of the individual parts of the earth's solid shell. In ordinary usage a rock means something hard and firm, but, geologically, a rock may be composed of a soft substance; thus a bed of clay or volcanic ash may be considered a rock as well as a mass of granite.

According to their mode of origin and the position of the masses with respect to the earth's shell, and to each other, rocks are divided into three main groups: the *sedimentary* or bedded rocks, formed by the deposition of sediments, chiefly by water (and to some extent by air); the *igneous* rocks, made by the solidification of molten material; and the *metamorphic* ones, produced from the preceding groups by certain processes which have wholly, or partly, destroyed their original characters and replaced them by new ones, and which are, therefore, conveniently considered in a separate group.

Thus we have three groups:

I. Sedimentary Rocks, sediments deposited by water or air.
II. Igneous Rocks, consolidated molten masses.
III. Metamorphic Rocks, secondary, from I and II.

CHAPTER XI

SEDIMENTARY ROCKS

The Composition and Character of Sedimentary Deposits

Sedimentation and Stratification. — If material of various degrees of fineness be dropped into still water the heaviest and coarsest particles will descend and reach the bottom first. Upon them will fall the next in size and so on to the top of the deposit, which will consist of the finest ones, thus making a regular gradation from bottom to top. If the water, instead of being still, were moving in a regular current the gradation would not take place wholly in a vertical direction, but in a horizontal one as well, the successively finer material being dropped farther and farther along the bottom. This material would be graded, but not stratified. If, however, the process be repeated, and the velocity of the current changed even to a slight extent, since in a foregoing part of this work (page 40) it has been shown how greatly the size of particles, which can be carried by moving water, depends on the velocity of the current, it will happen that, although the new deposit will be graded as before, at no point will its degree of fineness exactly correspond with that of the previous layer vertically under it. The two layers will be separated by a distinct juncture plane, on either side of which they will differ in texture; this is *stratification* and the juncture plane is called a *bedding plane*. It is clear that to obtain stratification there must be varying size of particles and velocity of current. Now as all currents, whether streams on the land or tidal ones in the sea, are constantly varying from place to place and from time to time, the deposits of the sediment, which they may carry and drop as they slacken, are always distinctly stratified, that is made up of parallel layers, or beds, which may differ in thickness, texture, and materials. A given layer may be part of an inch, or a hundred feet or more, in thickness, and it represents a period during which the conditions of deposition were uniform. A great thickness of very fine material indicates a prolonged interval of quite regular conditions and the probability of the deposit having taken place on the sea-floor or in some large lake. A single layer is known as a *bed*, or *stratum*, and a close examination may show that this is made up of

much finer layers, which may, indeed, be as thin as paper, and are known as *laminæ*. See Fig. 204. A collection of beds, lying concordantly above one another and deposited during a given geological period of time, is called a *formation*.

Matter carried and deposited by air currents may also be stratified, though generally much more rudely than when the work is done by water. Thus in a volcanic outburst the ashes driven by the wind may spread over a wide extent of country; the heavier and coarser particles fall first to be succeeded by finer and

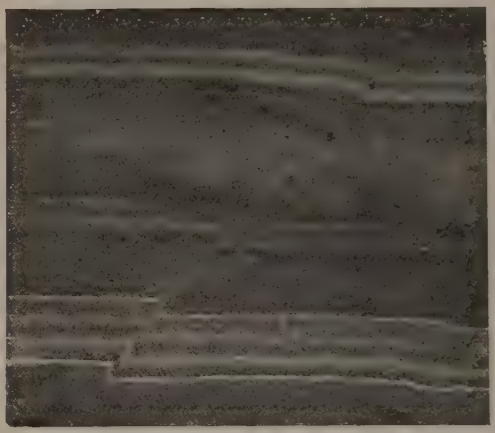


Fig. 204. — Thin laminæ composing part of a bed of sandstone, natural size. The displacement, or fault, has occurred since deposition.

finally by dust. This produces gradation, but if a new outburst occurs the coarser particles first falling will rest on the finer of the previous eruption and a continuation of this process will give rise to stratified beds, as may be seen in many parts of the Rocky Mountains.

But while deposits made by the wind, such as drifted sand or volcanic ashes, are sometimes rudely stratified, these are of small importance compared with the great masses of material which are, and have been in times past, carried and laid down by moving waters and, as shown above, such exhibit by their stratification the manner in which they have been formed. See Fig. 205.

Materials Involved. — The material which currents are able to transport and deposit, whether upon the land or in the sea, may have two modes of origin. It may be either the waste of the land, or matter produced by life in the sea. The first may be considered mechanical, the second organic in mode of formation. The waste of the land, through the destruction of previously existent rocks by various erosive processes, and its transport have been already treated in the foregoing part of this work, as has also the production of lime carbonate deposits by living organisms in the sea. They need, there-

fore, only this mention to show the contrast between them, one kind of material being of continental, the other of marine origin. There are other kinds of deposited material, such as rock salt, but

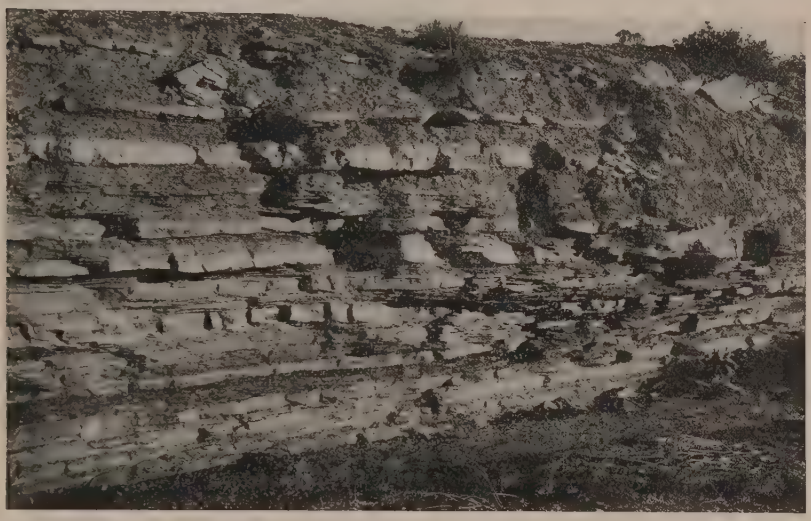


Fig. 205. — Regularly bedded sandstones and shales, near Pueblo, Colo. G. K. Gilbert, U. S. Geol. Surv.

these are of such minor importance that they need not be considered, at present, in this connection.

The land waste according to the size of the pieces, or particles, is roughly graded into *gravel*, *sand* and *mud*, or *clay*, as follows:

Gravel. — This is composed of material from the size of a pea up, and the individual pieces are termed *pebbles;* large loose fragments of rock are called *bowlders*. Pebbles which have suffered a long transport in the beds of streams or been much rolled by waves on the shores of seas and lakes have a characteristic rounded appearance. This depends also on the hardness of the substance composing them. The mineral quartz is one of the commonest substances forming pebbles on account of its hardness and durability. Sediments are sometimes composed of pebble-sized fragments which still retain their rough, angular shapes; in this case we judge that they have suffered little movement and are not far from their place of origin.

Sand. — Material composed of particles smaller than peas and yet sufficiently coarse so that it will not form a mass cohering when wet is known as sand. An ordinary sand would be like granulated sugar in fineness. It may be seen with a lens that the grains of coarser

sand, such as is found on sea-beaches, are rounded like pebbles by attrition, but in the finest sands they may be angular. Quartz is so common a substance forming sand that, unless otherwise stated, quartz-sand is understood. Many other minerals are found in sands, and on the beaches of coral islands the grains may be made wholly of lime carbonate.

Mud, Silt, Clay. — This is the finest part of the land waste and when dry it may form dust. It coheres when wet. As a sedimentary deposit it is found off shore, or in sheltered parts of estuaries, gulfs and bays where the slow movement of the water does not permit the transport of the heavier sand and gravel, or on the flood plains and deltas of rivers. As quartz is the characteristic mineral of sands so is kaolin that of muds and especially clays; as shown under the formation of soil, it is made by the decay of the feldspars of the rocks. In the destruction of the latter, since the quartz particles are heavier, while those of clay are extremely light and fine, there tends to take place a separation of the two by moving water; the quartz grains deposit first, forming sand, while the light clays settle later or are carried beyond into still water.

In summation, then, it is seen that the sedimentary deposits consist mainly of *sand, clays* and *carbonate of lime* and their varied intermixtures; gravels are of less importance in quantity though geologically of great interest, as we shall see later. Carbonate of lime deposits have been already treated in the chapter on the work of organic life. For glacial deposits see page 134.

Places of Deposit

The places where moving waters may deposit sediment can be divided into three: the land, the beach or area between the limits of average high and low tide, and the sea-floor. They may thus be classified as *continental*, *littoral* and *marine* deposits. Since the distinction between these is a matter of great geological importance they must be considered separately in some detail.

Continental Deposits. — The formations made upon the land by moving waters may be divided, according to their origin, into the following classes:

Desert Deposits of Arid Regions.
Piedmont River Deposits.
Basin Deposits of Humid Regions.
Sub-aërial Delta Deposits.

Each of these is of sufficient importance to demand some consideration, as follows:

Desert Deposits. — It has been previously shown, page 75 and following, that in all the continents interior drainages exist, caused by the excess of evaporation over rainfall. In such regions the land waste of the slopes of the basin constantly tends to move toward the more central parts and form deposits. It may be moved by rivers into permanent lakes, like Great Salt Lake and the Caspian Sea, slowly filling them up, or in times of rainfall temporary streams may spread out in thin sheet-floods over lower level areas, giving rise to temporary lakes (playas), in whose waters the sediments brought down may settle. Thus, through the continued action of rain wash and streams, aided by wind drift in times of dryness, the desert basins tend to fill up by deposits, which may become very thick, though at times and in places a reverse action by the export of material by the wind may thin them. Such deposits often contain layers of salt and gypsum as characteristic features, for reasons explained under salt lakes, and are apt to have a red coloration, as explained on page 161. See also work of the wind, page 13.

Piedmont River Deposits. — Where a young and lofty mountain range is undergoing extensive erosion it may happen that the rivers draining it become so heavily loaded with sediment that when they issue upon the piedmont belt (piedmont, foot of mountain) of country below their slackening current is unable to carry it all, and that part of the burden in excess of transporting power is deposited. In this portion of its course a river may, therefore, be aggrading, instead of eroding, and in times of flood its deposits may be widely spread over the adjacent country. Through the continued action of this process through a long period of time extensive deposits of sands and clays of great thickness may be formed. It is illustrated by formations lying upon the Great Plains and other tracts of country at the foot of the ranges of the Rocky Mountains' tract in western North America, in similar ones in South America upon the Pampas east of the Andes, and upon the piedmont plain of India at the foot of the Himalayas.

It used to be considered that these deposits (of the so-called Tertiary period) in western North America, whose fossils indicate them to be of fresh-water origin, had been laid down in extensive lakes then existing, but more extended study has shown that, while in part this view may be true, it is not a necessary one to explain them, since, as indicated above, they may be equally well formed by aggrading rivers, and that they have been made for the greater part, if not entirely, in this manner. Ultimately, if not saved by some intervening geological process, such as subsidence and covering by new sediments, such deposits in their turn must be eroded and carried away into the sea, the final depot of land waste.

Basin Deposits of Humid Regions. — In several of the continents basin-like depressions occur of variable extent and depth. Where the climate is arid and the rainfall consequently small these may give rise to interior drainages, as previously described. But if the rainfall of the region is considerable and in excess of evaporation, as discussed under lakes, these depressions, if deep, may give rise to lakes, such as the Great Lakes of North America, or, if very shallow, to wide swampy regions covered more or less completely at times with shallow water, like the basin of the upper Amazon and its tributaries. Such lake basins must obtain important deposits from inflowing streams, and may eventually be filled up, while the shallow swampy areas receive muds and clays from the outstanding waters of flooded rivers, and these are mingled more or less with organic matter from the decay of the vegetation which flourishes abundantly in such places. This swampy condition with resulting accumulation of river sediment may be indefinitely maintained if the basin is a region of continued subsidence. Though deposited in water such sediments are to be regarded as continental in origin, since they occur in hollows of the land surfaces. Not only are such deposits forming now, but they have been made extensively in times past, as we shall see later on

Delta Deposits. — The deltas of rivers represent so much land reclaimed from the sea or from a lake. The structure of the deposits is similar in both cases except that in the lake they are influenced by feebler waves and currents. Lake deposits have been considered in the foregoing section; what follows relates chiefly to deltas formed in the sea. The process begins by the deposition of sediments on the sea-floor; gradually these are built up on the front of the advancing delta until water-level is reached, and they then become land. The low-lying land is flooded in times of high water and more material laid down, and this continues until, in a vertical direction, a balance is reached between upbuilding in periods of highest flood and erosion at other times. Meanwhile, in a horizontal direction the delta is advancing seaward. Thus we see that a delta consists of a mingling of marine, littoral and continental deposits, and this is because it is situated in the debatable zone where land and sea struggle for mastery. The structure of a delta is shown in Fig. 206. The finest material is carried farther out and forms beds horizontal, or nearly so, which are known as the *bottomset* beds. Down the slope of the advancing delta are dropped the coarser sediments which make the inclined *foreset* beds. As stated above deposition also happens on top of the delta forming the *topset* beds which

are horizontal, or nearly so. Thus the foreset and bottomset beds are marine deposits, the topset beds may be largely land, or continental ones, while the littoral or beach zone is of minor importance. The deltas of great rivers like those of the Mississippi and Nile are

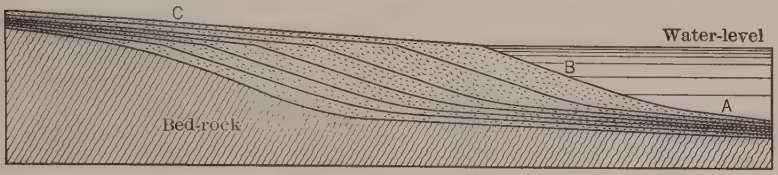


Fig. 206. — Illustrating section of delta built out in quiet water, of constant level. *A*, bottomset beds; *B*, foreset beds; *C*, topset beds. After Barrell.

built out in epicontinental seas on the submerged continental platforms, and in such cases of wide extent the difference of angle of slope and distinction between the foreset and bottomset beds mostly disappears. It has often happened that such shallow seas in times past have been filled by delta deposits which are, therefore, as we shall see later, of great geologic importance. It has already been mentioned in the discussion of subsidences of the earth's crust that the deltas of large rivers are commonly areas of subsidence and this, as shown by the thickness of sediments exposed, has frequently

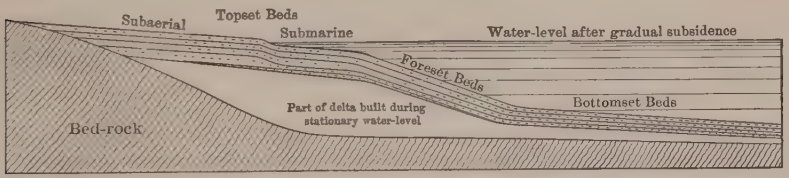


Fig. 207. — To illustrate conditions in a subsiding delta. A portion of the delta built during a period of stationary water line shows below. Through subsidence the water line has advanced to the left. The topset beds are partly subærial and partly submarine in origin. The foreset and the bottomset beds are relatively thin; compare with Fig. 206. After Barrell.

happened in the past. When a delta is subsiding, in contrast to one which is stationary, the up-building in a vertical direction increases at the expense of its horizontal extension; if the movement is pronounced the latter may be small.

In a *subsiding* delta the river currents tend to become more sluggish through decreasing grade, and the flooding of it more frequent. This results in a greater increase of material dropped upon the topset beds; the latter may thus become the chief contributors to the delta growth. If the area of the latter is great it may thus happen that the volume of land deposits, formed by the topset beds, may be vastly greater than that of the foreset beds which build out the delta's front. This relation is shown in Fig. 207. Consequently a delta, which is grow-

ing upward because of a subsiding foundation, tends to form dominant topset beds of continental nature; a delta growing outward because of a stationary one tends to form a greater volume of subaqueous beds.

Littoral or Beach Deposits. — The beach is defined as the area lying between average high and low tides. If the slope of the land to the sea is sharp it may be a very narrow zone, or in the case of sea-cliffs be wanting. If the inclination of the land is very gradual it may be of wide extent and consist chiefly of areas of salt marshes and tidal lagoons exposing mud flats at low tide. Such are well shown in the shallow sounds of North Carolina back of the barrier beaches and in the wide estuaries of Delaware and Chesapeake Bays. See page 99. Over these areas sands and muds are laid down as deposits, but generally along the shore, where the waves are cutting into the land and the beach or littoral zone is very narrow and exposed to the rush of the waves and tidal currents, only the coarser material such as gravel and sand are able to accumulate. Coarse sand and gravel, then, are the most characteristic features of beach deposits, and they cannot be of great thickness, for, if the land is building out into the sea, they must give place to land deposits and be buried under them, or, if the sea is encroaching on the land, they must yield to marine sediments and be covered by them. The importance of this will be seen when the geological structure known as a nonconformity is discussed later.

Marine Deposits. — The most active region for the deposit of land waste on the sea floor is in the shallow water, extending from the average limit of low tide out to the depth of 100 fathoms and thus upon the continental shelves, and also in the basins of epeiric seas (page 103). Over these areas the deposits are largely *terrigenous* (of land origin), consisting chiefly of sands and muds brought into them by rivers or formed by the waves gnawing on the coasts. The finer, lighter muds tend to extend farther out into deeper water, and may be met 200 miles from land extending down the slopes of the ocean basins. These marine deposits have already been described under the work of the ocean, page 103 and following, and need no further mention.

Enormous deposits, chiefly of carbonate of lime, have also accumulated on the sea-floor in times past through the agency of living organisms, and are forming at the present time. The character of these deposits and the conditions necessary to produce them have been stated under the geological work of organic life, pages 179 and following. It need be only remarked that the occurrence of such deposits is, in general, indicative that the seas in which they

were laid down were of clear water and possessed moderate to warm temperatures.

Consolidation of Sediments. — The stratified rocks are commonly in a very different condition from that in which they were laid down as sediments. Were it not, indeed, proved by the stratification, the contained fossils, and other features, it would be difficult in many cases to recognize their origin; to perceive in hard dense rocks the soft clays and sands they originally were. The causes of consolidation are many, and often complex. For one thing there is the long-continued and heavy *pressure* exerted by masses which may be many thousand feet in thickness. Another important factor is the deposition of material from solution in the spaces between the grains which *cements* them together. There is, in greater or less degree, a constant leaching of material from the upper layers by percolating waters and a transfer and deposition of it at lower levels.

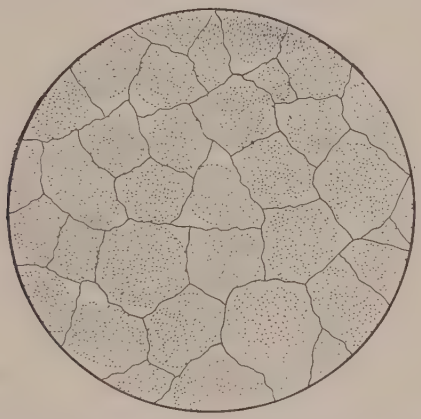


Fig. 208. — Section of sandstone (quartzite) under the microscope. The dotted areas are the rounded sand grains; the clear ones the silica deposited about the grains binding them into rock.

The most common cementing substances thus deposited in the rock-pores are carbonate of lime, silica, and oxide of iron. The interstices may become almost entirely filled with cement, as illustrated in Fig. 208, and the sediments thus converted into very firm solid rock.

The interior heat of the earth rising into such masses of sediments may aid in some degree to consolidate them by quickening the chemical and mechanical activity of the diffused waters which deposit the cement. And, finally, since the conversion of sediments into rock must be a slow process, *time* is an important element in the

case. Thus we observe that, in general, where the more recent sediments have been converted into land surfaces they exhibit much softer and more friable stratified rocks than the older ones. It must not be understood, however, that this process of cementation takes place only under the sea, for on land also the same process of solution, transfer to lower levels, and redeposition can be going on.

Kinds of Sedimentary Rocks

The different kinds of sedimentary rocks depend upon the nature of the sediments from which they are formed and the degree of consolidation, or compactness, which they have assumed. Thus, calcareous muds on drying may form a *chalk*, through pressure and cementation they become *limestone*, while the latter through certain agencies to be described in a later chapter and known as *metamorphism* may become densely hard and crystalline and is then called *marble*. The discussion of the stratified rocks which have been subjected to metamorphism is, however, deferred to that chapter in which this subject is treated; here only those cases are considered where the sediments have been consolidated by pressure and cementation as previously described. The chief sediments and the rocks they yield are, then, as follows:

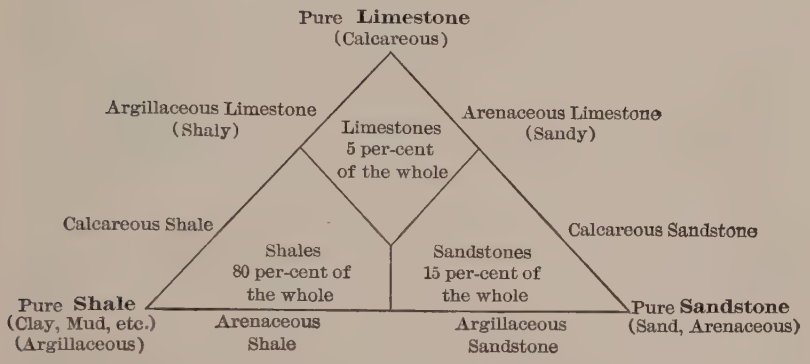
Sediments	Compacted strata, as rocks
Gravel	Conglomerate
Sand	Sandstone
Silt and clay (mud)	Shale
Lime deposits	Limestone

Gradations of Rocks. — It must not be imagined that the different kinds of rocks mentioned above are always sharply defined from one another as clear distinct types. This is very far from being the case. Just as muds grade through sand into gravel, and pure lime deposits into muddy ones, so may the various rocks formed from them grade into one another.

At this point it may be well to explain the usage of certain terms frequently employed in connection with sediments and stratified rocks. Of the finer deposits, or muds, clay is the most important representative; the word clay is of Anglo-Saxon origin, its adjective is *clayey*, the word corresponding to the latter derived from the Latin is *argillaceous* (from the Greek, argillos, clay). Similarly the adjective *sandy* has its Latin equivalent in *arenaceous* (from arena, sand —

the place where gladiatorial combats took place was so called because covered with it). The adjective limy, little used, has its counterpart in *calcareous* (from the Latin, calx, lime, limestone). These adjectives, argillaceous, arenaceous, and calcareous, are constantly used with reference to the sediments to which they belong and the rocks composed of them.

The gradations of the various kinds of stratified rocks into one another may be illustrated in the following diagram:



We are, therefore, accustomed to speak of calcareous sandstones, shaly limestones, etc., as indicated in the above diagram. The percentages in it give the relative estimated proportions, in each kind, of the total volume of all sedimentary rock; thus shales are sixteen times as abundant as limestones.

The characteristic features of those stratified rocks which are of greatest importance are the following:

Conglomerate. — The rock consists of pebbles or fragments held together by a base or cement of some kind. The pebbles, which compose the gravels from which these rocks are formed, are generally rounded. Quartz is the most common substance constituting them. Such pebbles may vary greatly in size, from a fraction of an inch to a couple of feet, or more in diameter. The appearance of a conglomerate is shown in Fig. 209. When the contrast of pebbles and cement is clearly marked, such rocks are sometimes called *pudding-stone*. When the rock is composed of angular fragments, which is sometimes the case where the material has suffered no transport, or only a short one, it is called *breccia*. Some conglomerates show by their characters, especially by the grooved and striated surfaces of the pebbles and the facets ground upon them, that they are ancient bowlder-clays, or tills, the morainal deposits of glaciers and ice-caps of past geologic ages. See page 134.

Sandstones. — These are usually quite even in grain and vary from friable to firm, according to the strength of the cement. In the red and brown varieties the latter is mainly oxide of iron; in the white, buff, gray, or pale brown, carbonate of lime; the question of

Fig. 209. — Conglomerate; the pebbles in this case are about the size of an egg.

their solubility has been already discussed, page 152. Sandstones are generally very porous rocks; 30 per cent of their volume may, indeed, consist of interspaces between the grains; they are, therefore, favorable strata in which to find artesian water. See page 148.

Arkose is a variety of sandstone which contains much unaltered feldspar. Its occurrence indicates that the component material has not been long exposed to weathering and has, therefore, probably not been transported great distances. It is thus more likely to be of continental, rather than of marine, origin, and to be produced by the breaking down of rock in lands with cold, arid climates rather than in those with warm humid ones where rock decay is rapid.

Graywacke. — This is a sandstone-like rock of a prevailing gray color composed of grains of various minerals and tiny fragments of other rocks. It is really a very fine-grained conglomerate, into which it not infrequently passes by increase in the size of the particles. It may also be of continental origin.

Shale. — This name is given to compacted muds and clays which possess a more or less thinly laminated, or fissile, structure. This parting is parallel to the bedding and is the result of natural stratification. Where shale beds have been subjected to folding and pressure, by crumpling of the crust, they assume a slaty cleavage which is distinct from stratification; the rocks are then slates, not shales, and will be discussed under metamorphic kinds in a following chapter. Shales are soft rocks, can be cut with a knife, and are apt to be brittle, and to readily break up into small chips. They show a great variety of colors from light to dark; in the latter case organic matter is present. Like clay, of which to a greater or lesser degree they are composed, they yield a characteristic odor when breathed upon. Unlike sandstone they tend to be impermeable to water.

Limestones. — The chief varieties of the carbonate rocks are *limestone proper* (essentially carbonate of lime, $CaCO_3$); *dolomite*, in which more or less of the lime has been replaced by magnesia to form the dolomite molecule $(MgCa)CO_3$, and *chalk*. These, and some of their sub-varieties, such as coquina, have been described under organic life, page 179 and following, where their origin is treated. Limestones are usually gray in color, varying from pale gray to black, dependent on the amount of organic matter they contain; sometimes they are yellowish or brown. They are generally very dense, compact rocks. They can be usually distinguished from other rocks which they may resemble by the readiness with which they can be scratched, or cut, and by their effervescing when treated with acid.

Characteristic Features of Sedimentary Rocks

In addition to the ordinary stratification which these rocks exhibit as a proof of their mode of origin they also possess other features, some of them minor ones, it is true, but none the less of significance, which enable us to determine the places where the sediments were deposited and the conditions under which the deposition took place, and to thus throw light upon the geological history which they record. Some of the more important of these features may be tabulated as follows:

Fossil Remains of Former Life.
Foot-prints.
Rain-drop Impressions.
Mud-cracks.
Tracks of Animals.
Ripple- and Rill-marks.
Cross-bedding.
Conglomerate Structure.
Oolitic Structure.

Fossils. — It is a common and well-known fact that the stratified rocks contain in variable amount the remains of animals and plants inhabiting the earth in former times. Sometimes these consist simply of the *impressions* of the organisms in the rock, sometimes in the actual *preservation* of their *hard parts*, such as bones and shells, and sometimes in the complete *preserval* of the whole *organic structure* by its entire change into stone (petrifaction), particle by particle as the organic matter decayed or was removed. Great diversity in the fossils of the rocks is found in several ways, and for obvious reasons. Thus they may vary according to the kind of rock, or, as it is said, change according to the rock facies; the kinds of animals that live in muds differ from those inhabiting sands, to a certain extent, and thus sandstones are liable to contain different fossils from shales. Fishes, which are free-swimming animals inhabiting both salt and fresh water, might furnish fossils in nearly all the different kinds of deposits, either continental or marine, while the bones of land animals would be expected in the former rather than in the latter, especially in sandstones. Also the fossils found in the earlier rocks are of very different kinds from those of the strata formed in later geological periods, and we learn by attentive study of this fact that there has been a constant evolution of life upon the earth from very simple to more and more complex types of organic structures. And finally, just as we know that the associated animals and plants of one part of the earth (its fauna and flora) differ from those of another part, so do the fossils of one region differ from those of another region. The further back in the rocks we go, however, the less do we find this difference marked, since the nearer do we approach to the less modified and simpler types of marine life.

All these are facts of the highest importance, and the manner in which they are used in deciphering the past history of the earth and its inhabitants will be set forth in detail in the second part of this book.

Foot-prints, and Rain-drop Impressions. — These are features not infrequently found in stratified rocks, and the conditions under which they are formed appear to be as follows. The tracks of large vertebrate animals made in muds and clays of the land surfaces of today when soft, as in the time of spring rains and floods, become later in the season, especially in arid and semi-arid countries, baked to an almost brick-like hardness and may endure for several years before they are effaced. The same is true, in lesser degree, of the tracks of birds, small mammals and the pits made by the rain-drops of a passing shower. This could hardly occur where the deposit was

kept soft and frequently washed, as in humid regions with much rainfall or on mud-flats constantly subjected to the action of the tide. But on the mud-flats of river plains and deltas, and on the shores of interior basins of arid or semi-arid regions, we can imagine such impressions formed, hardened, and then covered by deposits blown by the wind or swept by the waters of the next flood-time and thus preserved. They are thus essentially features of continental deposits and will only rarely occur in those of the littoral regions of the sea, where, possibly in the mud-flats at the heads of estuaries, conditions favorable for their production, such as unusually high tides, might sometimes occur. Since impressions in sand generally do not retain their shape or are quickly effaced, it is evident that these prints must be usually made in mud or muddy sands to be permanent and this means that those of former ages will be found chiefly in *shale* or very shaly sandstones, as this is the rock-form of compacted muds and clays. Examples of a foot-print and rain-drop impressions in shale may be seen in the second part of this book. It is, of course, clear that such impressions could not be found in true marine deposits.

Mud-cracks. — What has been stated above of foot-prints is quite as true of mud-cracks. Soft muds left exposed by the recession of high water dry and crack into polygonal forms, as illustrated in Fig. 210. Further exposure to the sun bakes and hardens the blocks. During the dry season these are often covered and preserved by wind-blown silt or sand. In other instances, at the next period of high water, these cracks will be filled with the coarser sediment first deposited, and the whole record buried and preserved by succeeding deposits. After the whole series of deposits has been hardened into rock, usually with subsidence beneath the sea and subsequent emergence, the layers of shale which the muds and clays form may be exposed by erosion, quarrying, etc., and will then exhibit these mud-cracks. It may happen that in taking up the rock-layers that the soft shale beds may break away leaving the filling of the mud-cracks projecting from the lower surface of the overlying layer, thus furnishing a natural cast of the cracks. As in the case of foot-prints it is obvious that the most favorable places for their occurrence will be on the flood plains of rivers, on the wide flat shores of shallow interior lakes, and less prominently at the upper margins of shallow estuaries of the sea and especially under arid or semi-arid conditions of climate where time for sun-baking and hardening occurs between periods of flood-water. They are thus characteristic features of continental deposits, minor and restricted ones

of littoral deposits, and in marine deposits will be generally wanting.

Under certain conditions, however, which have sometimes occurred in the geologic past, the recession of stretches of very shallow sea-waters, through other causes than the tides or infilling by sediments, has resulted in the drying and

Fig. 210. — Mud-cracks, delta of the Colorado River. G. K. Gilbert, U. S. Geol. Surv.

cracking of marine sediments, especially of limy oozes, but it is to be noted that the structure still signifies a continental origin. Thus mud-cracked limestones are not infrequently observed.

Submarine Tracks. — Other markings and structures are observed in the stratified rocks, which by study and comparison with similar features found in modern sediments, are referred to the tracks made by marine animals, such as crabs walking on the bottom, to the trails left by worms crawling, and to the filling of burrows dug by such animals in the deposit. They can occur only when the material has a tenacity adequate to retain the impressions until covered by the next sedimentation; it must, therefore, be neither too soft nor too crumbly. Sand mixed with considerable clay, giving rise to shaly sandstone, is the most natural medium. Such impressions on a beach subjected to the ebb and flow of the tide and the action of waves could, in general, not be permanent; hence their occurrence is indicative of marine deposits formed especially in shallow water.

Ripple-marks. — If one observes a sandy bottom in shallow water it will be frequently noticed that the sand has been thrown up

into a series of small parallel ridges by the action of the waves. These are known as *ripple-marks*. While they may also be formed in sand on land by the action of the wind, as on sand-dunes, see Fig. 5, they are especially characteristic of wave action in shallow water. They are not directly heaped by the waves, but are caused by the oscillatory motion which these give to the water, and, while generally formed in depths of less than 100 feet, they may corrugate the bottom, it is stated, in very fine sands up to 600 feet after heavy storms. Such furrowings may be preserved by later deposits and when consolidated into stone give the rock surfaces a characteristic appearance, see Fig. 211, when split or exposed by erosion.

Fig. 211. — Ripple-marked sandstone.

Wave-marks occasionally seen on the surface of strata are the curved lines of material washed up on the beach at the inshore edges of waves, while *rill-marks* represent the little diverging channels cut by the returning under-tow in passing over pebbles and other obstacles in the sand, or by rain water running over exposed flats. These are indicative of littoral and continental deposits, though it is possible that somewhat similar markings may be also æolian in origin.

Cross-bedding, or Oblique Lamination. — It is frequently observed in strata composed of the coarser detritus, such as conglomerates and sandstones, that the laminæ of particular beds, instead of

being parallel to the general planes of stratification of the series, are inclined to them, often at considerable angles and perhaps curved as well, as shown in the illustration, Fig. 212. This structure is known as *cross-bedding*, or oblique lamination. It usually indicates rapid deposit in shoal water by quick and shifting currents and is liable to occur in the foreset beds (page 260) of deltas, bars, spits and barrier beaches where the material is dropped down the forward slope of an advancing deposit. It may happen in rivers, lakes and the shallow waters of the sea and thus be found in continental, littoral and marine deposits. It is also the characteristic structure of wind-built sand-dunes where the material is rapidly shifted about and

Fig. 212. — Cross-bedding in sandstones. The large scale on which it occurs indicates a probable æolian (dune) origin. Walnut Canyon, Ariz. J. K. Hillers, U. S. Geol. Surv.

commonly deposited on inclined surfaces. It may thus be æolian in origin and, therefore, again found in continental deposits. The cross-bedding of certain sandstones of the Colorado region, and of the chalky limestones of Bermuda have been considered to have this æolian origin.

Concretions and Concretionary Structure

Concretions. — Stratified rocks in many places contain numerous inclusions of a different nature from that of the material enclosing them. These inclusions are apt to be rounded, and nodular in

form; some occurrences are quite spherical, others flattened, ovate, elongated, ring-shaped, or compound and exhibiting odd and fantastic shapes. They may be a fraction of an inch in diameter or many feet. The shapes of some are shown in Fig. 213 and the mode of occurrence in Fig. 214. They are often arranged in parallel layers. On breaking them open it is often found that the globular mass consists of matter aggregated about some object as a nucleus. Masses of this kind are known as *concretions*. In composition they are different from that of the main rock mass in which they lie, and are formed from one of its minor constituents; thus in chalk and limestone they are composed of silica; in sandstone of iron oxide or

Fig. 213. — Concretions from clay beds, Portland, Conn.

carbonate of lime; in shale of carbonate of lime or sulphide of iron. While some are very pure, they often contain large amounts of the rock-material, and in some cases the planes of stratification can be seen passing through them. Their origin appears to be due to material in the rock having gone into solution, and then for some reason having been steadily redeposited around certain centers as nuclei, thus building up the concretions.

Sometimes the bodies of animals or leaves of plants decaying in the sand or mud appear to have been the determinant cause of the formation of concretions, and to have served as the nuclei about which they collected. On splitting open

such concretions remarkable fossil imprints of ferns, insects, marine animals like shrimps, fishes, etc., may be obtained. Or sometimes, when they attain huge dimensions, the shells and bones of large animals may be found enclosed in them. In other cases some inorganic substance, such as a grain of sand, may have formed the nucleus, while in others no definite nucleus can be found. In some con-

Fig. 214. — Concretions in clay, Los Angeles, Cal. R. Arnold, U. S. Geol. Surv.

cretions cracks occur in which mineral matter of another kind has been deposited, seaming the surface with a polygonal net-work of veins; these are known as *septaria*. Iron-oxide concretions are not infrequently hollow, and more or less filled with sand. See also Fig. 18.

Flint and Chert. — Flint is a dark gray to black, very hard and compact substance occurring in irregular nodules, or concretions, in chalk. It is composed of silica, SiO_2, with a little chemically combined water. An impure flint, occurring in a similar way, in limestones, is known as *chert;* it is sometimes seen in parallel layers and lenses in the rock. The silica composing these substances appears in some cases to have been derived from the hard parts of certain organisms living in the sea-water, such as sponges, radiolarians, teeth of worms, etc., which have gone into solution and been redeposited. Flint is a substance of considerable interest because, on account of its hardness, homogeneity, and lack of cleavage, it has been used so extensively from prehistoric times down to the present by primitive peoples in the manufacture of implements and weapons, and for its employment in striking fire. Until a comparatively recent time, when percussion caps were invented, great battles and the fate of nations were decided by flint-lock guns. It has been observed that in the weathering and decay of certain Paleozoic limestone formations in the Southern States nodules and plates of flint are formed which may accumulate thickly on the surface. The chemistry of this process is not well understood.

In some places considerable masses of flint-like rocks occur on a scale which appears much too great for them to be explained by the origin mentioned above.

The varieties are sometimes called *jaspilite* (Lake Superior region), sometimes *novaculite* (Arkansas), and sometimes other names are given to them. In some instances they are believed to have been formed from silica chemically precipitated from solution; in others their origin is uncertain.

Concretionary Structure, Oolite. — Concretions may become so numerous in a rock stratum that its entire mass is composed of them, giving rise to concretionary structure. While this has been observed in sandstones and in iron ore deposits, as in the Clinton ores of eastern North America, it is mostly seen in certain limestone rocks. The concretions are generally minute, like small shot, and the rock in appearance resembles fish-roe, from whence it is

Fig. 215. — Pisolite, showing concretionary structure. Natural size. Bohemia.

called *oolite* (egg-stone). A variety with larger concretions (Fig. 215) is known as pisolite (pea-stone). The oolite structure is not rare; indeed it is much more common in limestones than is generally realized.

On the shores of Great Salt Lake at the present time the sand is observed to consist of minute spherical concretions, like fine bird-shot, of carbonate of lime deposited from the lake waters. Similar sands are forming about some coral islands; such sands if compacted and cemented would form oolite, and in some places this formation of the rock is now taking place, thus throwing light on its origin in the past.

Dimensions of Beds; Overlap; Relative Age

Area and Form of Beds. — It is theoretically conceivable that if all the lands were beneath the sea a world-wide stratum consisting

of deposits by marine organisms might form and on re-elevation of the lands be everywhere found upon them. No instance of this kind is known and the teachings of geological history, as shown later, inform us that it has not taken place. On the other hand, beds of mechanical sediments, such as sandstones and shales, imply land surfaces from which they are derived and basins in which they are laid down; it is obvious that their areal extent must be limited by the borders of the basins next to which they must thin out and disappear. In geometric form, then, a bed must be lens-like, lenticular, thicker near one border than on the other, and commonly extremely flattened; in ground plan it need not be circular, but is usually much elongated and irregular. As a general, but not invariable, rule it is found that the coarser the material composing a stratum is, the smaller the area which it covers; thus conglomerates may die out rapidly in a few miles, or even less, and coarse sandstones may have the same inconstancy, while on the other hand, beds of shale and limestone have been observed to cover thousands of square miles. Also, dependent upon the law of sedimentation, see page 255, it is found that beds are thickest and coarsest near the source of supply and thin out and become finer in texture as one recedes from it. Thus, coarse sandstones are observed to grade into finer ones and these into shales. It is sometimes stated that beds of stratified rock, if not changed from their original position, when elevated to form land-surfaces, are parallel and horizontal. From what has been mentioned above it is clear that this is not absolutely true; yet the scale on which the beds form unsymmetrical lenses is usually so large that, generally, in the exposures, even over long distances, they may appear to rigorously follow this rule. See Fig. 205.

That the strata are not always laid down horizontally may be readily seen where cross-bedding (previously mentioned) occurs, and especially in the foreset beds of small deltas, bars, etc. The inclination of such beds may be as much as 10° to the horizontal. Since the great extended beds of sediment have a one-sided lenticular form with the thickest edge next to the land, as they are piled on one another, the planes of stratification must have a gentle inclination seaward. But the scale on which this occurs is often so great that, as mentioned above, we may not perceive it.

Overlap. — It is often observed in a series of strata that the edges of some beds extend for distances beyond those of beds below them, where the lower ones thin out and disappear. This relation is known as *overlap* and the manner in which it originates may be understood by reference to the diagram, Fig. 216. This gradual advance of the sediments upon one another (or their retreat) is of

interest, because it marks the position of ancient shore lines, and indicates a sinking or rising of the land with shifting of the shore lines, or, possibly, the sea itself may rise or sink. Overlap may also occur on a small scale in the filling by deposit of a basin with sloping sides. It must not be confused with nonconformity.

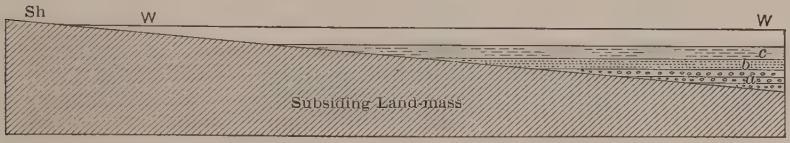


Fig. 216. — Diagram to illustrate overlap. On a sinking land, as the water, *WW*, continually moves inland on the shore, *Sh*, the successive beds of sediment *a*, *b*, *c*, are laid down more and more to the left, the edges of successive upper and newer beds overlapping those of the older and lower ones. On a rising land this relation would be reversed.

Thickness of Sediments. — It has been customary to ascribe great thickness to accumulated beds of sediments, or in other terms to stratified rocks, in certain places, especially in mountain ranges. It is very common to find them measured by thousands of feet; 5,000, 10,000 and 15,000 are not uncommon, and in some regions even greater thicknesses have been ascribed to them; thus, the strata which now compose the Appalachian Mountains are held to be 30,000 feet thick, while those of the Alps have been placed at 50,000. It is obvious that if we accept such great thicknesses as correct, since the great bulk of the land-derived sediments is deposited near shore, it must follow that subsidence of the sea-floor also occurred to permit of their accumulation. For close to the shore we do not find water of any such depth — 30,000 feet, indeed, marking the deepest parts of the ocean. And even though these maximum thicknesses assumed may contain, as they usually do, marine deposits of carbonate of lime in large amount, in addition to the terrigenous material, subsidence would be just as necessary. But, while undoubtedly subsidence and the accumulation of sediments to great thicknesses, many thousands of feet, have occurred, it is at least questionable whether in the extreme cases, such as those mentioned, all the different data necessary for an accurate result in measuring the thickness have been taken into account. If the stratified rocks at the bottom of a series of strata, apparently accumulated to vast thicknesses, are of a character similar (limestones, shales and sandstones) to those much higher up, or near the top of the series, it is improbable, for several reasons, that the whole was ever more than 15,000–20,000 feet thick.

An error may be made in estimating the maximum thickness of strata in that the initial inclination to the horizontal and the overlap of the beds, mentioned above, have not been sufficiently regarded. This has been recently urged by Chamberlain and Salisbury and the effect of it in causing error is illustrated in Fig. 217. On the other hand this idea must be used with caution for it assumes that in a thick formation the beds are chiefly *foreset* ones, deposited with a considerable angle of inclination, but in a broad and thick formation made by sub-

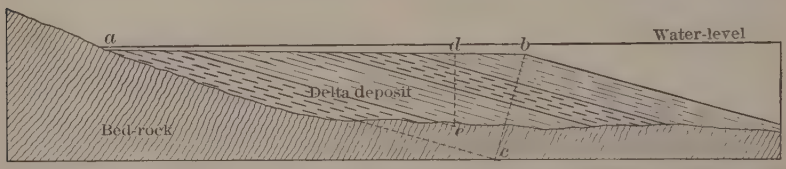


Fig. 217. — To illustrate apparent, as compared with real, thickness of strata. The figure shows a delta deposit composed of inclined foreset beds. The real thickness of the formation is *ed*. The apparent thickness *cb*, obtained by multiplying the distance *ab*, the exposed edges of the uplifted formation, by the sine of the angle of inclination, *cab*, is evidently much too great. (Modified from Chamberlain and Salisbury.)

sidence the *topset* beds are the dominant ones, and these are deposited, as a rule, with exceedingly gentle angles of inclination. If the tilting of the upturned and eroded beds is steep there is less error introduced by the customary method of estimating their thickness, while if they are only gently inclined the idea involved in the figure may be taken into account.

Relative Age of Beds. — In a series of beds of horizontal strata piled upon one another we assume that the higher a bed is in the set the younger it is in point of age. This seems so obvious as to need no further demonstration, yet it is the basis of all our deciphering of geological history, and upon it, in fact, the science of evolutionary paleontology has been built. This substructure of geology is so humble and close to the ground that it is often overlooked in the contemplation of the edifice which has been erected upon it; for the beginner, however, it should not be lost sight of. If we should conclude, however, that this rule is invariable, in all places and under all conditions, that an upper stratum is younger than one appearing below it in horizontal position, we should fall into serious error, for there are some remarkable exceptions to it, as will be shown later on.

Deformation of Strata

While over wide regions the stratified rocks appear to be lying, in a general way, in the horizontal position in which the beds were laid down, and to have been raised to form land surfaces, sometimes to great heights, without serious displacements, it is a matter of common observation that in other places, notably in mountain

regions, this is not the case. Here on the other hand, we find the strata inclined, often at high angles, thrown into folds, contorted, bent and often more or less broken. All such displacements may be included under the term of *deformation of strata*, which will now be described. The most probable causes for this phenomenon will be deferred until later, when mountain ranges, in which it is so prominently displayed, are treated; only the structures themselves being here considered.

Folds: Anticline and Syncline. — Study of the strata, by methods to be presently mentioned, shows that in many places they have been corrugated into folds. Sometimes these are on a small scale and can be readily seen, Figs. 221 and 222; often the folding is on such a great scale that only here and there in cliffs, rock outcrops, etc., are portions of a fold exposed; in them the strata simply appear inclined, but by noting the inclination and following the outcrops of particularly distinguishable layers, sometimes for miles, the immense size of the folds becomes clear to us. The manner in which strata have been folded and the scale on which it occurs may be seen by inspection of the adjoined section, Fig. 218, which has been worked out by geologists.

Fig. 218. — Section 12 miles long showing folding in the Appalachian Mountains, near Greeneville, Tenn. (Modified from Keith and Willis.)

With respect to folding, two terms are constantly used by geologists. In a series of folds it is evident that, like waves, they consist of alternate crests and troughs. The crests of the folds are termed *anticlines*, while the troughs are called *synclines*. This is shown in Fig. 219, where the up-folds *A* are the anticlines and the down-folds *S*, the synclines. Even if through erosion the original crests should be carried away and the whole reduced to a level surface *ll* we should still term the *A* portions below the surface anticlines and the *S* portions synclines, and in imagination reconstruct the missing parts. This should make it clear that anticlines and synclines *are not a matter of surface topography but of structure*. Although, as not infrequently happens, the original configuration of the surface should be reversed by erosion, as in Fig. 220, we should call the parts *S*, of the down-folds still left, synclines, and the up-folds between, anticlines,

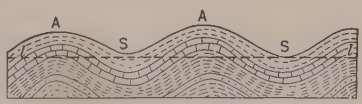


Fig. 219. — Diagram to illustrate anticlines, *A*, and synclines, *S*.

and infer the underground structure shown. A natural section through an anticline is seen in Fig. 221, and one through a syncline in Fig. 222.

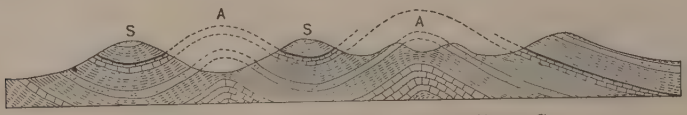


Fig. 220. — Anticlines, *A*, and synclines, *S*.

A simple mnemonic method, in regard to anticline and syncline, for the beginner to remember which is which, is to notice that the form of the letter *A*, the initial one of anticline, in itself represents a sharp crested anticline.

Fig. 221. — An anticline, broken at the top. In the foreground the outcrops of the eroded strata are seen dipping outwardly, from which the anticline structure could be inferred if the arch did not exist. Pembroke, Wales. Geol. Surv. of England and Wales.

Outcrop. — In considering the deformation of strata only the simplest case has so far been presented, where they have been thrown into a series of simple, upright, regular folds. But while this sometimes happens it is usual to find the nature of the folding much more complicated than this, and there are also other things in regard to folds which are of importance beside the consideration of a simple section across them. The varied kinds of deformation (or lack of it) which the strata have suffered in any region condition the *geologic structure* of that region, and it is a matter of the highest importance, in several ways, as we shall presently see, that the geologic structure should be, so far as possible, known for every country.

If the surface of the earth were everywhere naked bed-rock this would not be, relatively, so difficult; but since it has been greatly eroded and is so covered with earth and vegetation, or water, snow

Fig. 222. — A syncline, near Hancock, Md. C. D. Walcott, U. S. Geol. Surv.

and ice, the difficulties of the task have been enormously augmented. The manner in which we are able to discover the structure in a region is by a careful study and comparison of the *outcrops*, and by this term is meant those places where the underlying bed-rock comes to the surface and is exposed. See Fig. 221. If the ground were perfectly level and the strata horizontal the outcrop would be the flat surface of a rock stratum and we should learn little from it, beyond that fact. But if the ground is cut in any way, as by streams, we might be able to inspect the outcropping edges of the strata along the valley slope, as in Fig. 205. If the sides of the valley were trenched by ravines the line of outcrop would not be straight, but sinuous, retreating from the valley into the ravines and advancing on the spurs. See Fig. 223.

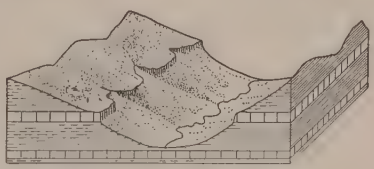


Fig. 223. — Section and outcrop of strata along valley.

If the strata have been inclined by folding and eroded it will fre-

quently happen that the edges of the harder, more resistant beds *outcrop* in projecting rock masses, or reefs. In mountain regions, the higher up we go, the less soil there is apt to be, and the more outcrops, until eventually the rocky ridges themselves form vast outcrops. By study of the dip and strike of the outcrops of a region the geologic structure is determined.

Dip and Strike. — These terms may be defined as follows: *Dip is the angle of inclination of the plane of stratification with the horizontal plane. Strike is the direction of the line of intersection of the plane of stratification with the horizontal plane.* This may be illustrated by Fig. 224. Imagine *XYZ* to be the horizontal plane, and *ABCD* the plane of stratification of the inclined strata. Then the angle *DBF* = *HBG* is the dip and the direction of the line *AB*, referred to north and south, is the strike. Since two planes could be passed through *AB*, one dipping to the left, as in the diagram, the

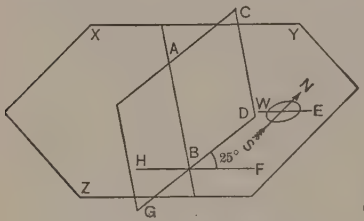


Fig. 224. — To illustrate dip and strike of strata.

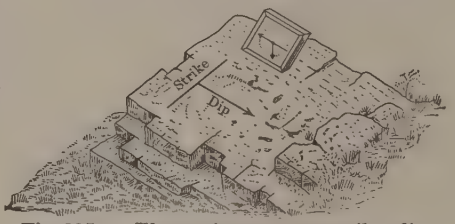


Fig. 225. — Illustrating outcrop, strike, dip, and determination of latter by clinometer.

other dipping to the right, with equal angles of inclination, it is customary to give the *direction of dip* to know which one is meant. Thus in a case like that shown in the diagram one would say, strike N. 30° W; dip 25° S. 60° W. Since the lines of direction of dip and strike are always at right angles, it is not really necessary to give the strike, if the direction and angle of dip are known; thus, dip 25°; S. 60° W. would be enough.

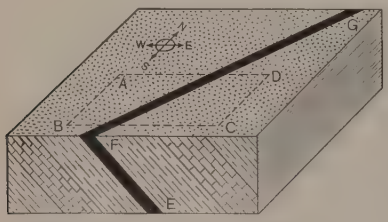


Fig. 226. — Use of dip and strike.

The direction of strike is taken with a compass furnished with sights, or whose containing box or bed-plate has straight edges aligned parallel to the NS points. The dip is taken with an instrument termed the clinometer, a pendulum swinging over a graduated arc, which measures the angle of inclination. The mode of use is shown in Fig. 225. For geologic purposes the compass and clinometer are usually combined in one instrument. The determination of dip and strike is not only necessary to unravel the geologic structure of a region, but has a practical use in other directions. Suppose that *ABCD* in Fig. 226 represents the bound-

aries of an area of land which is known to contain a bed of coal, marble, or valuable ore represented by *EFG* for example, and for commercial or legal purposes it is necessary to give a description of the bed and its exact position with reference to the property. The determination of its dip and the situation of its strike with regard to the boundaries of the plot furnishes this position. The determination of dip and strike when a reasonably good face of the strata is exposed, as in Fig. 221, is a comparatively easy matter, but where they are cut obliquely by erosion and are on sloping hillsides, it is much more difficult; the plane of stratification must be conceived from the data furnished by the outcrop and the desired results obtained by measurement of the imagined plane. If the strata are horizontal they have, of course, neither dip nor strike; if they are vertical, the dip is 90°, the strike, the compass direction of the outcrop upon the horizontal plane.

Dip and strike are represented upon geologic maps by a conventional sign ⊤, in which the direction of the cross bar, as placed on the map, indicates the direction of strike, while the upright leg points in the direction of dip. See Fig. 229. The length of the latter is also sometimes used to show the amount of dip; thus ⊢, with long leg, means a low angle of inclination, while ⊦, with short leg, a very steep dip; or the actual amount in degrees may be written in, thus ⊢ 30°.

Discussion of Folds. — Now that anticlines and synclines have been described and the means by which these structures, which are generally more or less eroded, are determined in the field by study of the dip and strike of the available outcrops, it is in order to further consider the nature and extent of folding. It is quite evident that a fold, up-arched, could not run in the direction of strike in-

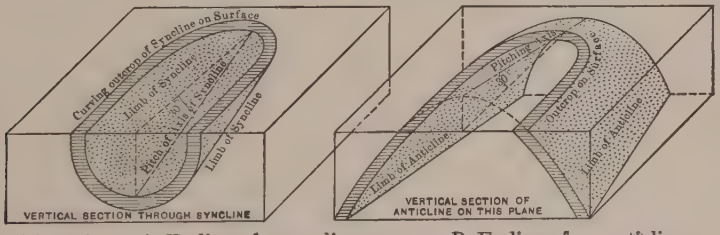

Curving outcrop of Syncline on Surface
Limb of Syncline
Limb of Syncline
Limb of Syncline
VERTICAL SECTION THROUGH SYNCLINE
Limb of Anticline
Limb of Anticline
VERTICAL SECTION OF ANTICLINE ON THIS PLANE

Fig. 227. — *A*, Ending of a syncline. *B*, Ending of an anticline.

definitely, or around the world; it must end somewhere. At the ending of a syncline we should have the structure seen in *A*, Fig. 227, and in *B*, that of an anticline approaching its ending, only a single stratum being shown in both. In the former the plane of stratification is warped into a form like the end of a boat; in the latter the boat would be overturned. It is evident that in both the strike of a hard projecting bed, as determined from its outcrops after the erosion indicated, would be elliptical, Fig. 228. The line of direction *XY* of the fold in Fig. 229 is the *axis* of the fold; in the syncline, at its end, this line *emerges* from the ground, in the anticline it *plunges* into it; the amount of inclination to the horizontal

of this line as the fold dies out is called the *pitch* of the fold. See also Fig. 227. Considered in regard to their relative length and breadth folds may vary from a dome-shaped uplift of the strata, whose strike

Fig. 228. — On a plain of marine erosion the outcropping edges of the strata are seen at the ending of a syncline, as shown by the curving strike and inward dip. Near North Berwick, Scotland; Geol. Surv. of Scotland.

would be circular, to extremely long narrow anticlines, whose strike is an elongated ellipse-like outline, and along whose sides the strike of the outcrops may be parallel for many miles, as in the Appalachian

Fig. 229. — Map of dip and strike showing underground structure of *A*, a syncline and *B*, an anticline.

Mountains. And, of course, the same may be true, in reversed structure, for synclines.

Inclined, Unsymmetric and Broken Folds. — In the cases mentioned above we have considered simple, regular, upright folds. If

through the center of a fold and its axis a plane be imagined to have been passed, as in Fig. 230, like the extended keel of a boat, we may term this the *axial plane* of the fold. In a regular, or symmetric fold, this plane is one of symmetry, that is the parts to left and right of it are symmetrically disposed, or each point on the left of the plane has its corresponding point at an equal distance on the right

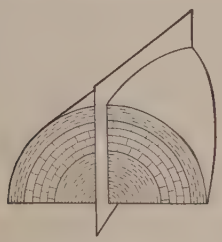


Fig. 230. — Upright symmetrical fold; axial plane vertical.

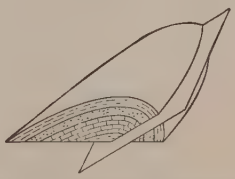


Fig. 231. — Inclined symmetrical fold; axial plane inclined.

of it. If the fold is upright the plane is vertical, Fig. 230. But it is very common to find that folds instead of being upright have been pushed over as in Fig. 231 until the axial plane is inclined; in

Fig. 232. — An overturned and nearly recumbent anticline. Panther Gap, Va. N. H. Darton; U. S. Geol. Surv.

this case the fold is said to be *overturned*. Such overturning may, indeed, go so far that the axial plane is nearly, or actually, horizontal; and the fold is then termed *recumbent*. An example of an over-

turned anticline is seen in Fig. 232. Similar cases may happen with synclines.

It is also very common to find that folds are asymmetric (without symmetry), that is they are not similar to right and left of the axial plane, which is not, therefore, one of symmetry, as in a regular fold. See Fig. 233. Such asymmetric folds may be upright, overturned, or recumbent, as with regular ones.

Finally, folds may be so sharply flexed (creased) that they may break to a greater or lesser degree, especially at the apex. And on breaking, the parts are liable to be displaced with respect to one

Fig. 233. — An asymmetric fold.

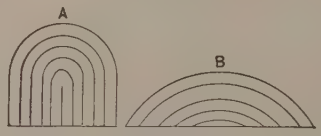


Fig. 234. — *A*, Closed fold; *B*, Open fold.

another, or faulted. Faulting, however, is so important a phenomenon that it deserves especial consideration, which will be given to it in a later place.

Other Features of Folding. — In addition to the important general characters of folds described above there are some others which at times and in places are of such interest that they deserve mention. Thus, when folds are so sharply flexed that the side limbs are in contact, as in *A*, Fig. 234, they are said to be *closed*, in this case the horizontal distance across the strata, or the width of the fold cannot be further reduced without squeezing or mashing of the beds; when not in contact, as in *B*, they are said to be *open* and the strata may be further folded without mashing. An example of a closed fold is seen in the overturned anticline, Fig. 232; of an open, upright anticline in Fig. 220.

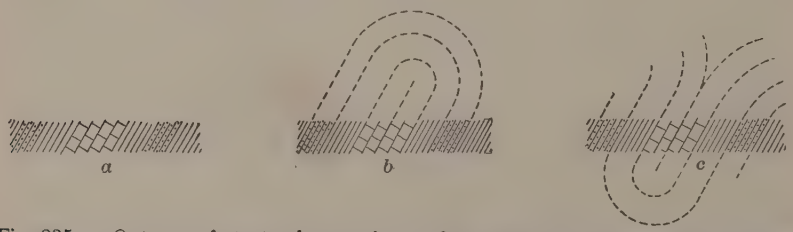


Fig. 235. — Outcrop of strata show as in *a*; they might be one series with inclined dip, or they may be closed isoclinal folds and receive various explanations, two possible ones being shown in *b* and *c*.

In *isoclinal* (equal inclination) folds the strata are compressed until on both sides of a fold, and perhaps throughout a series, they are parallel and have the same dip, Fig. 235, *b* and *c*. When such folds are cut away by erosion as in *a*, they may form structures very difficult of interpretation.

In some places, as in the Alps, where the compressive forces which produce

folds have been very severe, the strata may be underfolded and *fan-shaped* structures produced, as in Fig. 236.

In what has been said so far of folds they have been treated as simple structures

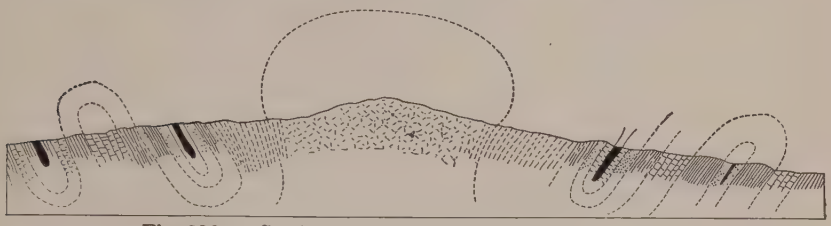


Fig. 236. — Section across the Alps, showing fan structure.

with true axial planes. But folds are frequently warped or bent, so that the flat axial plane of the regular fold is also warped or bent, not only in vertical, but also about horizontal directions. Folds may also branch or be compound, and thus a variety of most complicated structures be induced. And this is so both of anticlines and synclines.

Fig. 237. —A monoclinal fold.

Sometimes in the elevation of portions of a country, as in the Plateau region of the Southwest, the strata, through irregular uplift, are flexed as shown in Fig. 237. This is known as a *monoclinal* fold (one inclination), and may be compared to one side of an anticline.

Geosynclines and Geanticlines. — It has been previously mentioned, page 237, that long narrow belts of the ocean floor near the continental masses form concave tracts from 100–200 miles broad. Such down-warps of the earth's crust are evidently on a vastly greater scale than the folds we have been considering and which appear as mere minor and superficial wrinkles in comparison. Such great down-warps, which may be 1000 miles long and 200 broad, have been termed *geosynclines* by Professor J. D. Dana. There are facts which go to prove that correspondingly there are broad uplifts which are called *geanticlines*. The prefix is from the Greek word signifying the earth, to emphasize the scale of the phenomena. Such up- and down-warps may occur on the continents, as well as on the ocean floor. Thus the basin of Lake Superior has been held to represent a geosyncline, while the country northeast of it, in Canada, extending to Labrador, is believed to be a low, wide, slowly rising arch, which may represent a geanticline (see page 226). In the region about Cincinnati there is also a wide flat arch which forms a geanticline.

The geosynclines of the past, as well as those of the present, have been the great basins for the accumulation of sediments, like those which now form the Appalachians and the Alps. When later, by

actions which we shall study more in detail under mountain ranges, the accumulated beds are uplifted and compressed into folds, the whole series of folds, referred to the plane of the horizon, may form a compound, uplifted mass, which erosion thereupon carves into a mountain range with the aspect familiar to us. Such a mass of strata, laid down in a geosyncline and crushed by folding into a

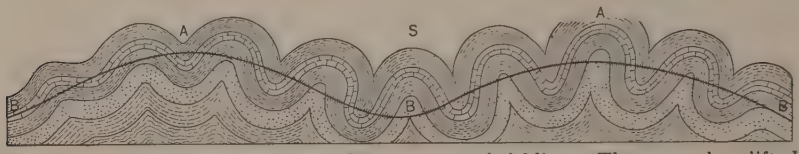


Fig. 238. — To illustrate terms used in compound folding. The general uplifted masses of folds *AA* are called anticlinoria, while the down-warped mass of folds *S* is termed a synclinorium. *BB* might represent a line of erosion, which would make *AA*, mountain ranges and *S*, an intermontane valley. It seems inappropriate to call a valley a synclinal mountain.

mountain range, has been termed by Dana, a *synclinorium* (from syncline and oros, Greek for mountain).

The term thus introduced by Dana has, unfortunately, been diverted from its original meaning and applied to a general syncline compounded of minor folds and contrasted with *anticlinorium;* see Fig. 238. It has thus become a term of structure, with the related idea of mountain-making, which the name expresses, relegated to a subordinate position, or entirely left out.

Unconformity and its Meaning

Definition. — It is not uncommon to find, on examining the stratified rocks exposed in outcrops in cliffs, valleys, and mountain sides, that one set of beds, whose parallel position, kinds of rocks and their relations, and the contained fossils prove them a continuously deposited series, are resting upon another set of rocks whose position and characters show equally well that they were formed at another period and under other conditions. Thus in the diagram, Fig. 239, the layers of strata *d* have been deposited at one period and under one set of conditions; they are, therefore, spoken of as a *conformable* series of beds, or a formation. Also the series of beds *c* are conformable among themselves; but it is quite evident that they are not conformable with *d*. To be in the position represented, events have happened to them which have not happened

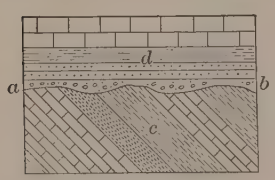


Fig. 239. — Section to show unconformity. *A* conformable set of strata *d* rest uncomformably upon another conformable set *c;* the surface *ab* is the unconformity.

to *d*. The two series are unconformable with respect to one another, and the surface *ab* separating them is called an unconformity, see Fig. 239, illustrated in Fig. 240. It is not intended by this statement that one should infer that the lower rocks, upon which the upper series of strata unconformably rests, should necessarily be also stratified, or sedimentary ones. The lower formation might be com-

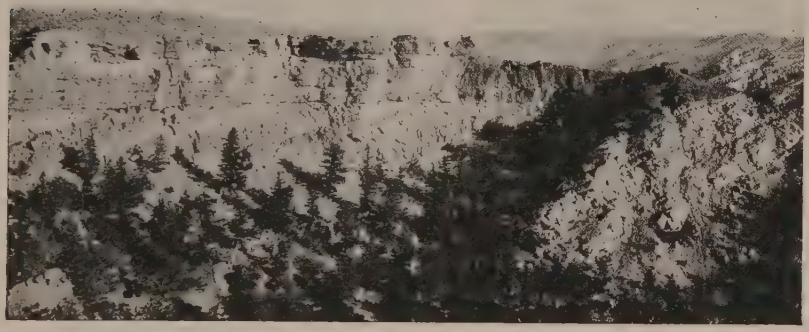


Fig. 240. — Angular unconformity. Basal Wahsatch conglomerate resting on upturned and eroded Laramie sandstone. Near Meeteetsie, Wyo. C. A. Fisher, U. S. Geol. Surv.

posed of igneous rocks, such as granite for example, or it might be composed of metamorphic ones, such as schists of various kinds, but the line *ab* would still exist and would be an unconformity. This will be better understood when we consider the geological history which an unconformity reveals.

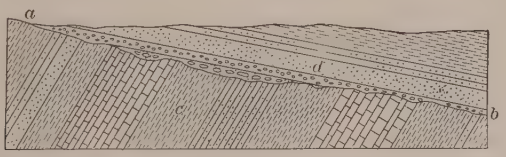


Fig. 241. — Angular unconformity; both series of bed tilted.

Geological History Revealed. — Let us take a case like that shown in Fig. 241, as an example. In this the following geological events are recorded. First, a period of quiet deposition in which the beds of the set *c* were laid down in horizontal position, or nearly so. The thickness of the beds, the kinds of rocks, their characteristic features and the contained fossils constitute the record for this

period. Next, a time of elevation when the sea-bottom became a land surface, accompanied by tilting of the strata, and followed by an interval when the uplifted strata were deeply eroded. For this period of uprise, tilting, and erosion we have no means of estimating the duration, except by the amount of erosion and by the record of succeeding events which mark its end. Not only were there no records, in the shape of sediments, etc., formed, but those of the previous period were wasted and more or less lost by erosion. There is, therefore, a gap in the geological record at this point and it is consequently often spoken of by geologists as a "*lost interval.*" Next in the geological history follows a period of subsidence when the eroded surface became sea-bottom again and received a new deposit of sediments, forming the conformable series of strata *d* in our diagram. The events of this time are again recorded in the strata as before. And finally, after a second period of uplift, the whole course of events is presented to us to be read as erosion progresses. The history here given may then be summarized as follows: first, deposition of strata; second, elevation and erosion; third, subsidence and fresh deposition; fourth, final elevation. And as a corollary we may add, and this is the important point about the matter, that, *an unconformity always represents a former more or less eroded land surface.*

Relation of an Unconformity to Kinds of Rocks. — Since an unconformity represents a submerged land surface it is of interest to consider the kinds of rocks that would naturally be associated with it. Evidence appears to prove that subsidence takes place slowly and, usually, with more or less varying pauses in the process. As the land lowers the sea works its way inward, due both to the submergence and to its own ceaseless gnawing at the coast-line. Where the land and sea meet there is generally a *beach*, and as the land subsides this beach marches inland at the edge of the encroaching sea. Every part of the newly made sea-bottom will have been passed over by this advancing beach. But the beach is that part of the bottom which is subjected to the ebb and flow of the tides, and to the onward rush of the waves and their returning undertow. Consequently, it is exposed to the action of strong currents, and only the coarsest of sediments, gravels and coarse sands can compose it. As the land subsides, all its superficial deposits, earth, stones, and rock decayed by weathering, will be worked over by the advancing sea, down to bed-rock, and perhaps deeper, and converted into beach material. The finer particles of the ground-up detritus will be swept out to sea to be deposited in quieter waters, and will form fine silts and muds. If one now imagines this state of affairs gradually passing inland, it is evident that the *first rock stratum of the new series, lying unconformably on the old bed-rock of the previous formation, will be a conglomerate or coarse sandstone*, since this is the consolidated form of the gravels and sand of the beach. Above this, we should expect the fine deposits of quiet water to appear as finer sandstones and shales, representing the silts and muds, succeeded or interspersed with marine deposits

of limestone. These relations are shown in the diagram, Fig. 242. Normally then, we should expect an unconformity to be marked by the presence of a conglomerate (or coarse sandstone), and this is often the case. While the above is the theory it is evident that in practice the result must depend largely on the nature of the disintegrated land material supplied to the waves and currents and the extent to which they can operate on it. The theory presupposes that the material is of unlike sizes and hardness, to obtain the variation in the beds. But if the land should consist of strata of soft and homogeneous character for example, as seen in areas composed of clays or shales, fine even-grained sediments might be formed which would yield no basal conglomerate. In the level interior regions of North America the flat-lying beds contain many unconformities which are not separated by conglomerates.

It is evident that if the process discussed above were to be reversed and the sea-bottom to *rise*, instead of to sink, the formations would also be reversed, and the sea-beach would be the *last* deposit left on the surface of the newly made land.

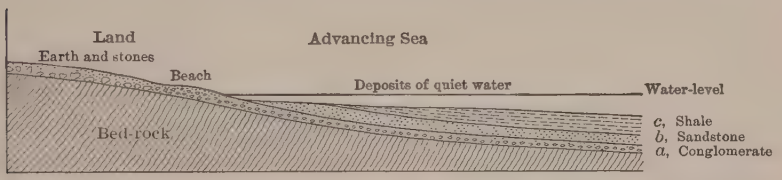


Fig. 242. — Diagram illustrating the normal order of deposits above an uncomformity.

If we should imagine this compacted into rock it would form a conglomerate of *emergence*, as contrasted with the one of *submergence*, described above. Being the first part of the new land to be attacked by erosion, and being still soft and unconsolidated, it would be the first material to be carried away and to disappear. Hence conglomerates of emergence are not apt to be found. But in small oscillations of the surface of land at, or near, sea-level, a conglomerate of emergence might persist long enough to be subsequently covered by the one of submergence. The two might then form, apparently, a single bed of conglomerate, through which would run the line of unconformity which might thus be non-apparent. This would furnish a case of what we might term a slight unconformity. Owing to the difficulty of detecting them, such conglomerates of emergence are apt to be overlooked where they might occur. This point will be referred to later.

Classification of Unconformities. — These may be divided into two main groups. In the first the lower formation, either by the tilting of the beds or by its being composed of non-stratified rocks, shows at once its non-conformity with the series of beds above it. This kind is illustrated by the diagrams (Figs. 239 and 241) previously given. It is sometimes called an angular unconformity (see Fig 240), because the stratification planes of the two series are at an angle; this term is good as far as it goes, but it does not cover the whole case, since, as mentioned above, the lower formation is not always composed of stratified rocks with distinct stratification planes, but may be of igneous or metamorphic rocks, which do not

show them. A more general term is needed and an unconformity of this class is here termed a *non-conformity*.

On the other hand, it may happen that the lower formation may be elevated, eroded, and submerged without material disturbance of the position of the beds. In this case the old and the new formations will have their stratification planes actually or practically

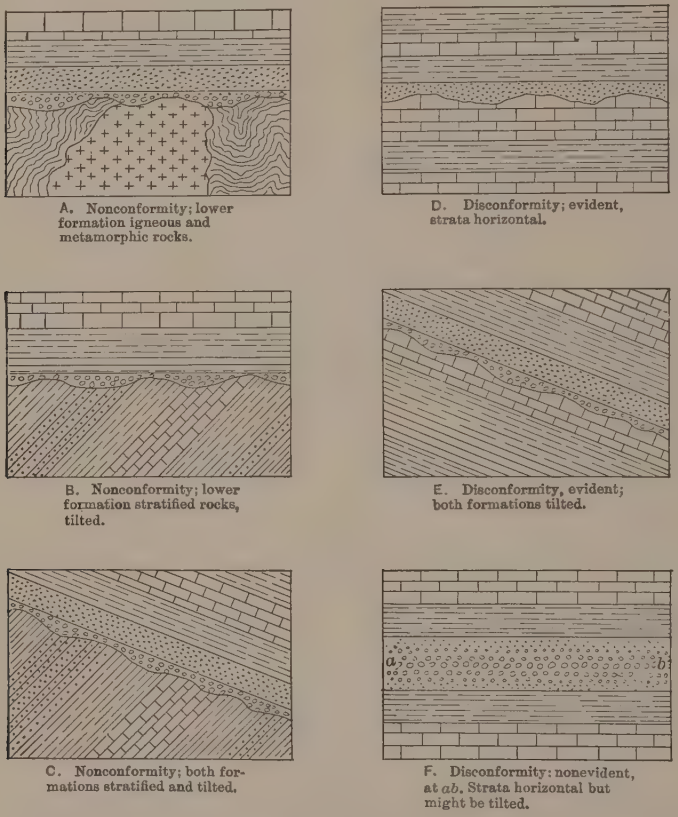

A. Nonconformity; lower formation igneous and metamorphic rocks.
D. Disconformity; evident, strata horizontal.
B. Nonconformity; lower formation stratified rocks, tilted.
E. Disconformity, evident; both formations tilted.
C. Nonconformity; both formations stratified and tilted.
a
b
F. Disconformity: nonevident, at ab. Strata horizontal but might be tilted.

Fig. 243. — Diagram illustrating various phases of unconformities.

parallel. This constitutes an unconformity of the second class, and, as it is desirable for a number of reasons that it should be distinguished from one of the first class, it has been termed a *disconformity*. Further, it may be that the erosion line between the two formations is an irregular one and thus clearly visible; this may be termed an *evident* disconformity. Or, owing to circumstances, the erosion line may run parallel with the strata and not be apparent; the unconformity must here be determined by the sudden change

in the nature of the fossils and by other things, such as the occurrence of thin basal sandstones and conglomerates, etc. (See in this connection what has been previously said regarding conglomerates of emergence.) In contrast with the previous one a case of this kind can be called a *non-evident* disconformity. We have, then, the following cases of unconformity:

Unconformity.

1. Nonconformity, two formations visibly different.
   a. Lower formation of rocks non-stratified, or apparently so.
   b. Lower formation of stratified rocks, tilted.
2. Disconformity, two formations in parallel position.
   a. Evident, erosion line clearly visible.
   b. Non-evident, erosion line not visible.

The different cases of these are illustrated in Fig. 243.

Also it may be added that in importance, in the length of time represented, in the greatness of change of life indicated by the fossils, and in the interest and variety of events recorded, the unconformities, in a broad general way, diminish from top to bottom of the diagram from *A* to *F*.

CHAPTER XII

THE IGNEOUS ROCKS

The igneous form the second great division of the different kinds of rocks which make up the crust of the globe. As their name implies, the presence of heat is an essential factor in their origin, and they may be defined as those rocks *which have been formed by the solidification of molten masses from within the earth.* Such molten masses, as have been mentioned under volcanic action, page 189, are commonly called *magmas*, a term we shall frequently use in speaking of them. These rocks are sometimes referred to as *primary*, because the material which composes the other kinds was originally derived, either from them or the original shell of the earth, which many regard to have been of the nature of igneous rock.

Distinguishing Characters. — The features of igneous rocks by which they may be distinguished from the sedimentary ones, whose characters have been given in preceding pages, and from the metamorphic ones to be presently described, consist partly in the relations which the masses exhibit towards other rocks and which we may term their mode of occurrence, and partly by characters which become evident when a rock-mass, or a piece of it, is closely examined. The different modes of occurrence of the igneous rocks will be described in the following section; with regard to those more minute features which are seen on close examination, the following are of importance. The igneous rocks do not, of course, contain fossils, nor, as a rule, do they show the parallel or banded appearance of the stratified rocks, for, in general, a surface in one direction looks like a surface in any other direction. They also have certain peculiarities in the minerals composing them and of the arrangement of these mineral grains (the *texture*, so-called) which distinguish them. Sometimes, indeed, they are more or less made of glass, which at once betrays their origin, since this substance could only be formed by the chilling of melted material. These features will be more fully described when the different kinds of igneous rocks and their classification are considered; we will first discuss the various ways in which masses of igneous rock occur.

Occurrences of Igneous Rocks

Intrusive and Extrusive Rocks. — There are two chief modes of occurrence of igneous rocks, the *intrusive* and the *extrusive*. In the former the magma, rising from depths below, has stopped before attaining the surface and has cooled and solidified, surrounded by other rock masses of the earth's outer shell. In the extrusive, the magma has attained the surface, come out upon it, and there solidified forming the rock masses. These are sometimes called *effusive* and sometimes *volcanic* rocks, though it is held by some that they are not always connected with volcanoes. See page 208.

With both intrusive and extrusive rocks there are variations in the mode of occurrence depending, in the case of the former, on the relations an intrusive mass may bear to the other rocks which enclose it, and in the latter on the conditions under which the magma was ejected. Following the course of the magma upward we will begin with the intrusive; but it should be first recalled that, since these rock masses were covered by previously existent ones at the time of their formation, they can only be exposed at the surface, and thus laid open to observation, after a period of erosion sufficient to carry away the cover and disclose their intrusive relations. In some cases, when intruded near the surface, this time interval may have been a comparatively short one; in other cases very prolonged, when the masses were deeply buried.

Intrusive Modes of Occurrence. — These are *dikes*, *intrusive sheets*, *laccoliths*, *necks*, *stocks*, and *bathyliths*. Several other modes of occurrence have been described and named, but as they have not yet been generally recognized as of the importance of those mentioned, they will, for simplicity's sake, be treated as modifications of them. The simplest form of intrusion is that of the dike and this will be considered first.

Dikes. — A dike results from the simple filling of a fissure in existent rocks by molten magma from below, which there solidified. Consequently, its extension in length and breadth is great compared with its thickness. It may "cut," that is pass through, rocks of any kind, igneous, sedimentary, or metamorphic; but in sedimentary ones it must traverse the planes of stratification at an angle; if parallel to them it is an intrusive sheet. As exposed on the surface it may be a few yards or many miles long; it may be a fraction of an inch, or many hundreds, or even some thousands of feet in thickness. An illustration of a dike is seen in Fig. 244.

The ordinary thickness of most dikes is from two or three feet up to twenty; the exposed length very variable. The course of a great dike in the north of England has been traced for over 100 miles. As we naturally think of a bed of stratified rock as in a horizontal position and call its departure from horizontality its dip, so we think of a dike as a sheet of rock in a vertical position; this is by no means always the case and the angle of inclination of the plane of extension of the dike with the vertical is called its *hade*. The direction of its outcrop or intersection with the horizontal plane is termed its strike, or *trend*.

Fig. 244. — Dike of trap-rock in granite. In this case the dike is less resistant and has been cut away by erosion, leaving a trench in the granite. Isles of Shoals, N. H.

Dikes may have attained the surface and given rise to outflowings of lava, or they may not, and have been exposed by later erosion. In some cases they have formed the canals feeding larger intrusive bodies above them, such as the sheets and laccoliths to be next described. In the process of erosion, it sometimes happens that the dike is more resistant than the surrounding rocks and is left projecting as a wall; sometimes less resistant and has become a ditch; from these features the name is derived, especially the more prominent wall, for dike means both wall and ditch. The rock of a dike is cut into blocks by fissures, and very commonly the blocks are columns lying perpendicular to the wall of the dike, like a pile of cord-wood, an arrangement whose origin is described later under columnar structure. Dikes occur in many places in more or less well-defined systems, and around volcanic centers are apt to be radially disposed.

Intrusive Sheets. — It is not uncommon to find, where intrusions of magma occur in stratified rocks, that it has been forced in layers between the beds. This most frequently happens where the beds are weak and easily penetrated, as in shales, thinly bedded sandstones and the like. Such a flat extended mass lying concordantly along the planes of stratification is known as an *intrusive sheet* of igneous rock, though sometimes it is spoken of as a *sill*. Such sheets may be a foot or so in thickness, or several hundred feet, and they may spread over many miles in area. An illustration of them is seen in Fig. 245.

Sheets may break dike-like across the strata and be continued along a new horizon. These intrusions may be distinguished from surface flows of lava, which have been buried by deposits of later sediments, by the rock composing

them being of the same hard firm nature at top and bottom, and by the overlying sediments being baked and altered by the intrusion. The surface of a lava flow is usually spongy, ropy, slaggy, etc., (see page 193) and a flow could, of course,

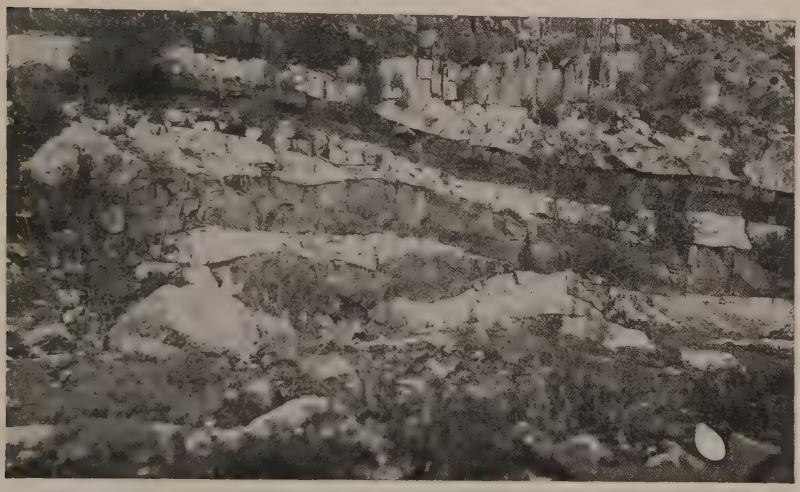


Fig. 245. — Intrusive sheets of igneous rock. Cottonwood Canyon, New Mex. W. T. Lee, U. S. Geol. Surv.

exert no action on beds not yet deposited upon it. Intrusive sheets are most liable to occur where larger, more important intrusions of magmas, such as laccoliths and stocks, have taken place, as accompanying features in the surrounding strata. In regions where thick intrusive sheets occur, and the strata have been broken, dislocated and upturned by faulting (see faulting), they may give rise to prominent topographic and scenic land features through the effects of later erosion. This is illustrated in the trap ridges of southern New England, northern New Jersey and in other places.

Laccoliths. — The laccolith in its typical development is a lenticular or dome-shaped mass of magma intruded into the sedimentary rocks between the bedding planes. It has a flat floor and is more or less circular in ground plan. If the supply of material in the formation of an intrusive sheet is more rapid from below than can easily spread laterally, the strata above will be uparched, as if by a hydrostatic press, and a thick lens of liquid rock will be produced, giving rise on solidification to a laccolith. The name is from the Greek, meaning cistern-rock. Such a mass may be a few

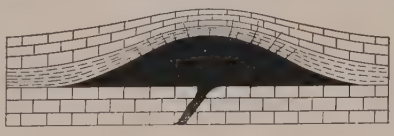


Fig. 246. — Section of a laccolith. The black area is the igneous rock.

hundreds of feet or a mile thick at the center, and a few hundreds of yards or several miles in diameter. In the uprise, the sedimentary beds above are usually more or less stretched, thinned, and broken. A section of a laccolith is shown in Fig. 246, and a photograph of one from which the cover has been removed by erosion, laying bare the mass of igneous rock, is seen in Fig. 247.

Fig. 247. — Bear Butte; a laccolith denuded of its cover and the igneous mass laid bare. The ring of upturned eroded strata is seen about its base. Black Hills, So. Dakota. N. H. Darton, U. S. Geol. Surv.

While the above statement gives the idea of a typical laccolith, many departures from this arrangement are found in the actual occurrences. In ground plan they may be circular, oval, or quite irregular, and instead of being symmetrical in section, like Fig. 246, they may be one-sided, or wedge-shaped. According to their degree of flatness, all transitions into intrusive sheets occur. They may also break across the strata in places like intrusive sheets. They may thin out into intrusive sheets, or be accompanied by them on the flanks of the arches, and thus be compound in structure. Such sheets may themselves swell out into inclined lenticular masses, or subordinate laccoliths. And in regions where the strata are being folded, areas of relief from pressure or, possibly, openings might form on the sides of the arches, see Fig. 248, which would permit the entrance of magma. This would give rise to inclined, doubly-convex bodies like that shown in Fig. 249. Laccolithic bodies of this character have been termed *phacolites* by Harker (from the Greek word for lentil + stone). It is sometimes questioned whether the magma supplies its own force in making the intrusion and in arching up the strata, or in other words is *aggressive*, or whether,

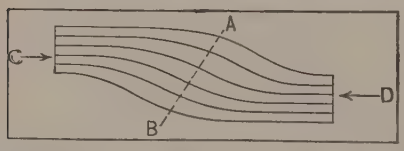


Fig. 248. — Strata being folded by compression *CD*, relief from pressure from overlying beds and spreading might occur in direction *AB*.

as indicated above, the force lifting the beds comes in some other way and the magma simply flows into the space opening for it, or the intrusion is, so to speak, *permissive*. But a study of the occurrences shows that in all probability both of these cases occur. In central Montana, where the strata are horizontal and undisturbed save by the intrusions, the magma must have acted aggressively, but in other places where folding and uplifts occur, the intrusions were probably permissive.

Laccoliths, more or less exposed by erosion, are conspicuous features in many parts of western North America, where they were first discovered by Gilbert in the Henry Mountains in southern Utah. Some of the best examples occur in Colorado, as described by Cross and they are also abundant in Montana. In places they are so aggregated as to make mountain groups. More recently they have been found in various parts of the world and thus appear to be a not uncommon form of intrusion.

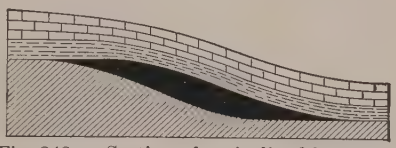


Fig. 249. — Section of an inclined laccolith, or phacolite.

Bysmaliths. — It may happen that an intrusion is so aggressive that what would otherwise be probably a laccolith may have its roof ruptured and driven upward by the magma rising like a plug through the strata. The vertical dimensions of such a mass may be much greater, compared with the lateral ones, than in a laccolith. A core-like intrusion of this character has been termed by Iddings, a *bysmalith* (Greek, plug-rock).

Chonoliths. — Finally intrusions of magma may be of very irregular shape and bear no definite relation to the stratified beds in which they occur, as do sheets, dikes, and laccoliths. They may be formed aggressively by the rising magma having ruptured and crowded aside the beds, or in regions of dislocated rocks by its having passively risen into irregular chambers forming for it. For all such irregularly-shaped bodies of injected rock Daly has proposed the name of *chonolith* (from the Greek word meaning "mold," used in casting metals, and rock.)

Necks. — When a volcano becomes extinct the column of magma, occupying the conduit leading to unknown depths below, may solidify and form a mass of igneous rock. Erosion may cut away a great part of the ashes and lavas of the cone, leaving this more solid and resistant rock projecting, as shown by the line *abc* in Fig. 250. Or, the level of erosion may descend into the rocks which form the basement on which the volcano is built, all of the ashes and lavas being swept away, and only this mass being left to mark its former site. Such a mass of rock is known as a *volcanic neck*, and a view of one may be seen in Fig. 251. It is commonly more or less circular in ground plan and may be from a few hundred yards up to a mile or more in

Fig. 250. — Section through a partly-eroded volcano, with volcanic neck left projecting.

diameter. The rocks about volcanic necks are apt to be fissured and filled with dikes, and in many cases, if stratified, with intrusive sheets. The significance of volcanic necks has been previously explained, page 202.

Fig. 251. — Alesna volcanic neck, Mt. Taylor region, New Mex. C. E. Dutton, U. S. Geol. Surv.

Stocks. — This term has been applied to large bodies of intrusive rock which, in the form of magma, have ascended into the upper region of the earth's crust, and there solidified. They have become visible only by extended erosion, and usually have a more or less circular or oval ground plan. Their outer surface, or plane of contact, cuts across the inclosing rocks, is more or less irregular, and the mass may widen in extent as it descends. Their size may be from a few hundred yards to a number of miles in diameter. Since they are apt to form protuberant topographic features through erosion they are sometimes, especially in Great Britain, called *bosses*. The distinction from a volcanic neck is not one of size alone, though necks tend to be smaller than stocks, but in that the term "neck" is employed only when there is evidence that extrusive volcanic activity has been connected with it. Some stocks were doubtless necks, but this cannot now be proved. The granite hills of New England, and of many other old eroded mountain regions are often largely composed of stocks, or bosses.

Bathyliths. — This word is used in a general way to designate huge irregular masses of igneous rock, which, underlying the sedi-

mentary and so-called metamorphic ones, or sometimes cutting through them, have been exposed by erosion. They are seen in the oldest exposed areas of the earth's crust, where they are characteristically accompanied or surrounded by metamorphic rocks, as in eastern Canada and New England, or in mountainous regions where they form the central cores of masses of the ranges, as in parts of the Rocky Mountains. They differ chiefly from stocks in their much greater size, as they are in some cases exposed over many thousands of square miles of surface.

While some stocks are clearly intrusive and have displaced the rocks whose site they occupy, the mode of formation of others and of bathyliths is still a subject of speculation. Some have held that they have attained their position by melting and assimilating the previous formation and thus replacing it, while others have urged the view that it has been ruptured, uplifted and driven out by the invading mass of magma and then eroded away. Various modifications of these views have been suggested, and while geologic science is not yet in a position to pronounce definitely upon their correctness, it seems probable that no one set process will explain all cases, and that at different times and places various ones have operated.

Extrusive Igneous Rocks. — The modes of occurrence of the extrusive igneous rocks have already been described in connection with volcanoes and extrusions of lava, and what has there been said in regard to them may be profitably consulted in this connection, page 191. For the sake of convenience the following summary is here given. There are two kinds of extrusions of magma, depending on the quantity and activity of gases contained in it; the *quiet* in which it outwells as a liquid and solidifies into rock, and the *explosive* in which it is more or less violently driven into the air and falls in the form of solid fragments.

Quiet Eruption: Lava Flows. — Magma which appears at the surface and outpours is known as *lava*. When solidified it is commonly spoken of as a lava flow, or extrusive sheet. Usually such outflows are in connection with volcanoes, the extrusions of a few volcanoes being, indeed, wholly of this nature, like some of those in Hawaii, but generally lava flows succeed, or alternate with projections of fragmental material.

In other cases it has been thought that they are not connected with volcanic eruptions, but have taken place as quiet outwellings from numerous fissures. This has sometimes occurred on a huge scale, as in the Columbia river region of the northwestern United States, in western India, and in the north of the British Isles. In the first two regions the repeated lava flows are thousands of feet in depth and cover areas of from 100,000 to possibly 200,000 square miles. This view of the origin of the Columbia lavas has, however, been disputed, as mentioned on page 208.

Not infrequently sheets of lava have sunk below sea-level and been covered by deposits, or they have originated on the sea floor and have been covered. Such buried extrusive sheets are distinguished from intrusive ones by the fact that they have not altered, changed or baked the sediments above them, and their upper surfaces usually show the structures common to the surface of lavas, such as the vesicular, scoriaceous and ropy ones described previously.

Explosive Eruption: Tuffs and Breccias. — When magma attains the surface in the canal of a volcano it may give rise to quiet flows of lavas as mentioned above, or, if its viscosity is sufficient and it is charged with vapors under great tension, it will give rise to explosive activity, and the material will be projected into the air to fall in solid fragmental form, as already described under volcanoes, page 200. Owing to the expansion of contained vapors, chiefly steam, the projected pieces usually have a more or less vesicular structure, and vary in size from large blocks to fine dust. According to size this material may be roughly classified as follows: pieces the size of an apple and upward are termed *volcanic bombs;* those the size of nuts *lapilli;* ones the size of small peas, or shot, *volcanic ashes;* while the finest is *volcanic dust.* The coarser material, the bombs, ashes and lapilli, falls around the vent and builds up the cone; the lighter ashes and dust, carried by air currents, tend to fall after these and at greater distances. The beds of coarser material thus produced are termed volcanic conglomerate, or, more commonly, *volcanic breccia,* while the finer is known as *tuff.* See pages 196 and 201.

Volcanic Tuff. — The rock formed by the consolidating of volcanic ashes and dust is usually light in weight, sometimes of a chalky consistency, sometimes quite hard and dense. It is of various colors, generally of light shades. When very fine and compact a tuff might be mistaken for the rock of a lava flow, but generally examination will show angular fragments in it and in some cases the tuffs contain excellent imprints of fossils; of leaves, twigs, etc., if the ashes have fallen on land, or of marine organisms, such as fishes, etc., if into water. If the ashes fell into water the tuffs may be well stratified and interbedded, perhaps, with shales and sandstones. It is here that gradations of igneous into sedimentary rocks may occur. Volcanic tuff was formerly called *volcanic tufa* but it is now customary to restrict the word tufa to deposits from aqueous solution, especially those of a calcareous nature. See page 157.

Volcanic Breccia. — This has a base of tuff more or less filled with angular pieces and bombs, and masses which are apt to be rounded. It often contains fragments of the rocks through which the conduit has been drilled. These characters distinguish breccias even when they are very hard and much changed later by processes which act upon rocks. Usually they are rather soft and easily attacked by erosion; the cement, or base, goes first leaving the bombs and contained masses projecting. In this way on the edges of cliffs oddly-shaped figures of erosion are produced, in regions where volcanic breccias are common, as in parts of the Rocky Mountains.

Tuffs and breccias are rocks of wide distribution, being found in all those districts where volcanic activity is being, or has been, displayed, and their presence is, indeed, one of the surest indications of its occurrence in former times in places where vulcanism has long since died out. We are thus able to recognize the former existence of volcanoes in various parts of the eastern United States and

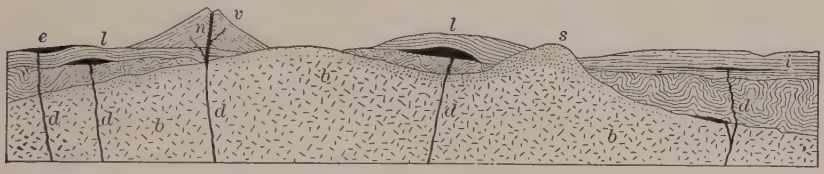


Fig. 252. — Diagram to illustrate the occurrence of igneous rocks; *b*, bathylith; *s*, stock; *n*, volcanic neck forming *v*, a volcano with tuffs and breccias; *l*, *l*, laccoliths; *i*, intrusive sheet; *e*, extrusive sheet; *d*, *d*, dikes. Horizontal distance shown thirty miles; vertical distance, three miles.

Canada, from Nova Scotia to Georgia. In the regions of the Rocky Mountains they are found in vast quantities, piled up in places thousands of feet in thickness, where, as in western Wyoming, serried mountain peaks have been cut from them by erosion.

Age of Igneous Rocks. — The determination of the geologic period when a given mass of igneous rock was erupted, or intruded, is made by observing its relations to the previously existent rocks with which it has come in contact. Thus, if one body of igneous rock, such as a dike, passes through, or cuts, another body of rock, it is the younger of the two. If it cuts across stratified beds it is younger than they are, and lavas, of course, are more recent than the rocks upon which they lie. If a sheet of igneous rock lying concordantly between strata has affected the beds both above and below (see contact metamorphism, page 329) it is younger than both. If the overlying beds are not changed the sheet may be a lava flow, see page 296, and older than they are. It is thus usually easy to tell what rocks an igneous mass is younger than, by examining its contacts with them, but much more difficult to say what ones it is older than, because usually the younger beds have been eroded away if the mass is exposed, or they still conceal it, or it may never have been covered. The age of the stratified rocks is, of course, determined by their fossils, and the endeavor is made to bring the igneous ones, which contain no fossils, into time relation with them.

Kinds and Classification of Igneous Rocks

Introductory. — Those features of igneous rocks by which the different kinds are distinguished have been already mentioned in a preliminary way in the discussion of the products of volcanoes,

page 190, but should now receive the attention which they demand in this place. Igneous rocks are divided into different kinds on the basis of two properties, first their *composition* and second, their minute structure, or *texture*. Each of these requires explanation.

Composition of Igneous Rocks. — Since igneous rocks are produced by the solidification of magmas it is evident that their composition will depend on the chemical composition of these molten fluids. It has been already shown, page 189, that a magma consists of two parts, volatile constituents, which are given off as water vapor, carbon dioxide, sulphur fumes, etc., and a non-volatile part, a molten flux, consisting chiefly of the oxides of certain metals and silica. Although the gaseous part is important, for reasons we cannot now consider, in rock formation, it is essentially the melted oxides which give rise to the rocks and are the chief and determining constituents of magmas. While it is evident that a molten magma cannot be analyzed directly by chemical methods, still, the kinds of oxides present and their relative proportions can be ascertained by analysis of the cold and solid rock. This has been done with many thousands of igneous rocks from all parts of the world and, in a general and rudely approximate way, the following results have been obtained, which show the composition of the magmas.

Silica, SiO_2, always present; may vary from 35–75 per cent.
Alumina, Al_2O_3, varies from nothing to 25 per cent.
Oxides of iron, (FeO and Fe_2O_3), usually both, 0–20 per cent.
Magnesia, MgO, 0–45 per cent.
Lime, CaO, 0–20 per cent.
Soda, Na_2O, 0–16 per cent.
Potash, K_2O, 0–12 per cent.

It must not be concluded from inspection of the above table that within the limits given any and all sorts of mixtures of these oxides can occur. As we shall see presently there are certain general laws governing their associations. It will also be noticed that there is one definite acid-forming oxide, silica, present, while the oxides of the six metals, aluminum, iron, magnesium, calcium, sodium and potassium, are, in general, bases. Since we have then an *acid* and *bases* in the magma, according to one of the fundamental principles of chemistry, there will be opportunity, under suitable conditions, for the formation of *salts*. What these salts are we shall learn later. Oxides of other elements occur in small or minute quantities, but are of so much less importance that they may be neglected.

Associations of Oxides in Magmas. — While there are many exceptions to this rule, it has been found to be generally true that large percentages of potash and soda (alkalies) in a magma are accompanied by correspondingly large ones of alumina and silica and with consequent small amounts of the other three metallic oxides. Conversely, large percentages of magnesia, lime and iron oxides are

apt to be associated, and these go with low silica; the alumina and alkalies being small or wanting. These reciprocal relations are of general fundamental importance in igneous rocks and it will be recalled that they have been pointed out before, page 190, since the nature of volcanic activity, and of the kinds of volcanoes, in large measure depend upon them. They may be expressed in a general way as follows:

Where SiO_2, Al_2O_3, $(NaK)_2O$ are high, CaO, MgO, FeO are low or wanting.
Where CaO, MgO, FeO are high, SiO_2 is low, and Al_2O_3, $(NaK)_2O$ are low or wanting.

Crystallization. — It is a familiar chemical experiment that if one places zinc in sulphuric acid diluted with water it will quickly disappear with evolution of hydrogen and in the place of the acid and the base (metal) the vessel will contain a salt, zinc sulphate, in solution. If the liquid be boiled down and concentrated to a certain point the zinc sulphate can no longer remain in solution, but will begin to appear in solid condition in the form of crystals. If the hot solution be allowed to cool, more crystals of the salt will be formed, since, in general, hot solutions can contain more salt than cold ones. In analogy with what has been stated above, a molten magma is to be regarded as of the nature of a solution; it contains silica, an acid-forming oxide, and metallic oxides, which are bases. If the magma cools with sufficient slowness these will unite to form salts, which at proper temperatures will take on solid form and appear as crystals. This will proceed as the temperature falls until the whole magma turns into a mass of solid crystal grains. The molten liquid has become *stone*. It rarely happens that the proportions of acid and bases are so exactly balanced in a magma, or the circumstances are such, that it is completely turned into salts; nearly always there is an excess of the acid, which appears as solid silica, SiO_2 (quartz), or of some of the metallic oxides (iron oxides, alumina, etc.), which latter may combine. Such solid compounds, salts and oxides, occurring in nature are *minerals* and we see from this that igneous rocks are, in general, composed of *mineral grains* of various kinds, and that these grains have crystallized from the magma.

Kinds of Minerals. — The more important of the minerals which form the igneous rocks are the following:

Feldspar Group	Ferromagnesian Group
Orthoclase Feldspar, $KAlSi_3O_8$	Mica, (Biotite) $K_2(MgFe)_2Al_2Si_3O_{12}$
Albite Feldspar, $NaAlSi_3O_8$	Pyroxene, $Ca(MgFe)Si_2O_6$
Anorthite Feldspar, $CaAl_2Si_2O_8$	Hornblende, $Ca(MgFe)_3Si_4O_{12}$
Nephelite, $NaAlSiO_4$	Olivine, $(MgFe)_2SiO_4$
Also Quartz, SiO_2	Magnetite, (Iron Ore) Fe_3O_4

Of these minerals, *feldspars*, *quartz*, *pyroxene*, and *hornblende* are the most important in forming igneous rocks and the student should, therefore, make careful note of them. For further details regarding them reference should be had to the appendix dealing with the minerals mentioned in this work. It will be seen by examining their chemical formulas, as given in the table above, that they are composed of silica and the six metallic oxides previously mentioned as forming the magmas.

Furthermore, since it was shown that the relative proportions of the oxides varied in the magmas, it is evident that the relative quantities of the minerals will also vary. Thus, a magma in which $(NaK)_2O$, Al_2O_3 and SiO_2 are the chief substances will form a rock consisting mostly of feldspars, while one in which CaO, MgO and FeO are high will make rocks containing largely or mostly pyroxene, hornblende and other *ferromagnesian* minerals, as they are called in allusion to the iron and magnesia in them, or mixtures of these minerals.

Thus it appears that igneous rocks vary in the kinds and relative amounts of the minerals which compose them, and on these variations, as we shall see later, depend mainly the different varieties of igneous rocks, and the manner of classifying them.

Texture. — While igneous rocks are distinguished and classified in one way by the *kinds* of mineral grains which compose them, they are also classified in another way by the *textures* which they may exhibit. By *texture* is meant the *relative size*, or sizes, of the component grains and their relation to each other. Thus, if the grains were as large as peas we should say that in texture such a rock was *coarse-grained;* if like ordinary loaf sugar, such a rock would be *fine-grained;* while, if the particles were so fine that they could not be discriminated by the eye and the rock appears like a homogeneous substance, we should say it was compact, or *dense*, in texture.

This evidently depends on the size of the particles, and that in turn depends at the *rate at which the magma cooled*. For if the magma is too hot, as explained above under crystallization, this process cannot take place and no crystals will begin to form until the proper temperature is reached; then they will commence to appear and, if the cooling is very slow, they will have time to grow to large size, giving a coarse-grained rock. But if the cooling is rapid, new centers of crystallization will be more and more forced to form, and, if the process is thus hurried, instead of fewer crystals growing to larger sizes, the rock will consist of a much greater number of smaller

particles, or will be fine-grained in texture. And with still more rapid cooling the particles may be so minute that the rock has the dense texture. Analogy will now carry us one step more; we could conceive that the cooling might take place with such great rapidity that the magma would solidify into a homogeneous substance before any crystallization, which consists in the molecules arranging themselves together to form definite solid compounds, could occur. In this event we should have *glass*, or a glassy, rather than a stony texture, as the result, a case which sometimes happens.

To sum up, then, we see that igneous rocks in their texture may be *coarse-grained*, *fine-grained*, *dense*, or *glassy*, and that this depends on the rate of cooling of the magma.

Porphyry: Porphyritic Texture. — In what has been said so far, regarding the texture of igneous rocks, it has been tacitly assumed

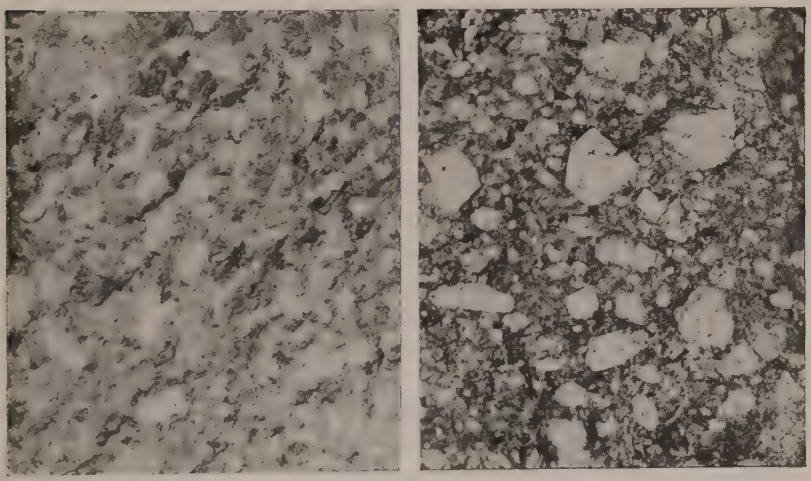


Fig. 253. — *A*. Even-granular Rock. *B*. Porphyry.

that the component mineral grains are, in any given rock, of uniform size, or that the rock is evenly *granular*, as it is called. This is, however, by no means always the case. For inspection of igneous rocks shows that in many cases they are composed of crystals of two sizes; larger, more distinct ones embedded in a matrix of much finer grains. An igneous rock having the latter texture is called a *porphyry*. Examples of the even-granular and porphyritic textures are seen in Fig 253, *A* and *B*. The matrix of a porphyry is termed the *ground-mass*, and the larger embedded grains, the *phenocrysts*

(evident crystals). The porphyries are a large and important division of igneous rocks.

The ground-mass (matrix) may itself vary greatly in texture: it may be medium-grained, fine-grained, compact, or glassy; most commonly it is fine-grained, or compact. And the phenocrysts may also vary widely; they may be of large size, as large as walnuts, or as small as grains of sand; they may be abundant, or comparatively few. But always there is this *contrast* between *sizes* of crystals, between ground-mass and phenocrysts, which makes the essence of a porphyry, and the student should guard against making it a contrast of *colors;* thus a rock consisting of grains of light colored quartz and feldspar, in which are embedded a few black crystals of mica, all grains being of about the same size, is not a porphyry.

Relation of Texture to Geologic Mode of Occurrence. — Since, as has been shown above, the texture of an igneous rock depends chiefly upon the *rate* at which the magma cools, it is clear that this in turn will depend most largely upon its final resting place. For it is obvious that an *intrusive* mass of magma, surrounded and blanketed above by other, older rock masses, must lose heat much more slowly than an *extrusive* one, poured out on the surface in the form of lava. Hence, as coarse-grained textures mean slow cooling, we naturally associate them with intrusive masses, and, conversely, regard the dense, or glassy types as belonging to the products of extrusion, the surface lava flows. But it is also clear that the size of the intruded mass will have much to do with the rate of cooling, since a very large mass cools more slowly than a small one. Thus, the great bathyliths and stocks are naturally coarse in texture, while dikes and intruded sheets tend to be much finer, or compact. On the other hand, it is easy to conceive that the central portion of an extremely thick lava flow might cool with sufficient slowness to afford a medium-grained type of texture, while a magma forced into a narrow fissure in cold rocks might be chilled so quickly as to assume a dense, compact, or even glassy one. Thus various modifications of the general rule can be easily imagined, according to particular cases, and yet this general rule, that the intrusive rocks are medium- to coarse-grained, the extrusive ones fine-grained to dense, is nevertheless true.

An important deduction, which follows from the above, is that the coarse-grained rocks, since they have been formed in depth, can only become visible at the surface after a prolonged period of erosion, which has been sufficient to remove the cover and expose the igneous mass.

With respect to what has just been stated the *porphyries* occupy a

somewhat intermediate position. It would carry us too far to discuss in this place the most probable causes for this type of texture, but, in general, one may say that the porphyritic texture is evidence of a rather rapid and variable rate of cooling and crystallization. Consequently, it is an infrequent feature in the great stocks and bathyliths, is much more common in the smaller intrusions, such as laccoliths, dikes and intrusive sheets, and is very commonly found in lava flows.

While the rate of cooling is the most important factor influencing the texture of igneous rocks, as discussed above, it is not the only one. The subject is too complicated a matter for detailed treatment in this work, but it may be mentioned that the chemical composition has also its influence; those magmas with low silica and much iron and magnesia tending to assume coarser grain than the ones composed of much silica, alumina and alkalies, under similar conditions of cooling. The reason appears to be that the former are less viscous, or more fluid, at lower temperatures than the latter, as already explained, page 190, and thus when they crystallize this mobility of the molecules permits the growth of larger crystal grains.

Also the presence of the included vapors which magmas contain, especially water vapor, increases the fluidity and promotes a coarser crystallization. This is very notably shown in certain places in intrusive masses, in cracks and fissures which have served as channels of escape for the gases, and which are now filled with large and even huge crystals of quartz, feldspar and mica. These very coarse masses are known as *pegmatites*, and from them are obtained the plates of mica which are used commercially.

In the case of a volcanic neck, the rock is apt to be comparatively coarse-textured for a small mass, because, by the constant upward passage of molten material to the surface, the rock masses surrounding the channel have become greatly heated, thus producing slow cooling in the last charge of magma which occupies the conduit and solidifies there when the volcano becomes extinct.

Classification of Igneous Rocks. — The different features by which the igneous rocks may be classified have now been explained. We have seen that they vary in the kinds and relative amounts of the mineral grains composing them, and that they also vary in texture. Both features are used to classify. Thus we may at once divide the igneous rocks into two groups on the basis of texture; one in which the mineral grains are sufficiently large to be identified by the eye alone, or aided by a pocket lens; and another in which they are too minute for this to be done. In the latter case further subdivision has to be carried out on the basis of color and general appearance and according to this the rocks are divided into *felsites* (light or medium colored rocks) and *basalt* (black or nearly black rocks). These have been previously explained. The group in which the grains are sufficiently large for the component minerals to be recognized (usually about the texture of loaf sugar) may be

termed *grained* rocks and can be subdivided on the proportions of the constituent minerals. They can be divided into two main groups, one in which feldspar is the predominant substance; and another in which it is subordinant, or lacking, and the dark iron and magnesia minerals (hornblende and pyroxene) are the chief components. Each of these may be further subdivided, in the first as to whether the feldspar is accompanied by quartz, or not, and in the second as to whether pyroxene or hornblende is the dominant ferromagnesian mineral. Further divisions are made as to whether the texture is even-granular or porphyritic. These various distinctions and the names of the different kinds of igneous rocks which they make are exhibited in the following table.

TABLE OF CLASSIFICATION OF IGNEOUS ROCKS

A. Grained, constituent grains recognizable. Mostly intrusive

	a. Feldspathic rocks, usually light in color		*b.* Ferromagnesian rocks, generally dark to black	
	With quartz	Without quartz	With subordinate feldspar	Without feldspar
Even-granular (nonporphyritic)	GRANITE	SYENITE	DIORITE (with hornblende) GABBRO (with pyroxene) DOLERITE (undetermined)	PERIDOTITE Pyroxenite Hornblendite
Porphyritic	GRANITE-PORPHYRY	SYENITE PORPHYRY	DIORITE-PORPHYRY	

B. Dense, constituent grains nearly or wholly unrecognizable. Intrusive and extrusive

	a. Light colored, variable; usually feldspathic	*b.* Dark colored to black; usually ferromagnesian
Nonporphyritic	FELSITE	BASALT
Porphyritic	FELSITE-PORPHYRY	BASALT-PORPHYRY

C. Rocks composed wholly or in part of glass. Extrusive

Nonporphyritic	OBSIDIAN, Pitchstone, Pumice, Scoria, etc.
Porphyritic	Vitrophyre (Glass-porphyry)

D. Fragmental igneous material. Extrusive

TUFF and BRECCIA (Volcanic ashes, bombs, etc.)

Method of Study. — The classification which has just been described is based upon what can be recognized by the eye, aided, perhaps, by a pocket-lens. It is thus termed a *field* classification and sometimes *megascopic* (Greek μεγά, great) in contrast to one based upon results obtained *microscopically*, by the study of

thin rock slices. In the latter method a chip of rock is ground flat with emery on a metal plate, then cemented to a piece of glass and the other side ground down, first with coarse, and successively with finer and finer emery powder until the section is as thin as paper. In this way the minute mineral grains composing the densest and blackest of basalts become transparent, and may be studied and determined under the microscope. See Fig. 254. In this study polarized light is used, and a general knowledge of minerals, of their crystal characters, and optical properties is necessary. It would require too much detail to describe further this mode of studying rocks, which combined with the examination of them by chemical means, has developed into a separate geological science, called *Petrology*, the science of rocks, but it should be stated that so much additional information is gained by these processes that the ultimate classification of igneous rocks is much more complicated than the simple scheme outlined above.

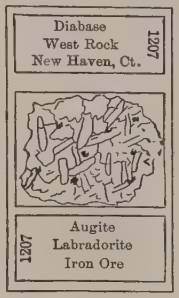


Fig. 254. — Thin section of a rock.

Granite. — As may be seen from the scheme of classification, this rock is composed chiefly of quartz and feldspar. It also generally contains in variable amount dark specks or flakes of mica, less commonly of hornblende, or both. It is the most important intrusive igneous rock, and appears to be one, if not the main, constituent of the basement part of the continental masses, or floor upon which the rocks of later sedimentary age were deposited. It also appears of younger age in the form of great stocks and vast bathyliths which have displaced these younger rocks. In these occurrences it is either in the form of true granite, or in a certain modification of it which we shall see later among the metamorphic rocks, and known as gneiss. Since granite is formed at some depth it is only after prolonged erosion that it appears at the surface, hence it is seen chiefly in those parts of the continents long exposed, and especially where crumpling and crushing of the shell has happened; that is to say, in mountain regions. There are many varieties of granite based on color, texture, etc. Its common occurrence is shown in the fact that there are few states in the Union, or provinces in Canada, which do not contain exposures of granite, and its use as a building-stone and for various purposes is well known.

Syenite. — This is like granite in composition and texture, but differs in containing little, or no quartz. Several varieties are distinguished, based on the character of the feldspar, and accompanying feldspar-like mineral. Thus in *syenite proper* the feldspars are alkalic, that is contain soda and potash, but little, or no lime. In another variety, in addition to the feldspars, a feldspar-like mineral, *nephelite*, $NaAlSiO_4$, is present, and the rock is known as *nephelite-syenite*, or foyaite. Another rare type contains corundum, Al_2O_3. These syenites are not common rocks, nor, as a rule, do they occur in very large masses compared with granite. A variety of this class of igneous rocks, one in which the feldspar

known as labradorite and composed of soda and lime is the chief constituent, is called *anorthosite*. It is of importance, although the number of known occurrences is not many, from the large and sometimes vast masses which it forms. Areas of it are found in eastern Canada, from Labrador to Ontario, covering hundreds and even thousands of square miles; in the Adirondacks, Minnesota, Norway, etc.

Diorite, Gabbro, Dolerite. — These are usually more or less dark colored, heavy, massive rocks. The iron-magnesia silicate, in the coarser varieties, forms dark to black specks and grains which equal, or overbalance, the lighter colored ones of feldspar. The kinds are based on the nature of the ferromagnesian mineral; if it is hornblende the rock is *diorite*, if pyroxene it is called *gabbro*. The distinction between the two ferromagnesian minerals, given in the appendix, is often very difficult to make, and not infrequently impossible. In this case the term *dolerite* may be used, signifying a rock with an undetermined ferromagnesian component equal to, or in excess of, the feldspar. This class of rocks, while very abundant in intrusions, is not commonly found in the extensive bathyliths and stocks in which granite occurs. They are more often seen in smaller stocks, intrusive sheets, dikes, necks, and sometimes forming the inner part of heavy extrusive masses. When rather fine-grained, appearing as dark heavy rocks, occurring in dikes and sheets, they are sometimes called *trap*, from a Germanic word meaning stairs, in allusion to the step-like appearance the exposed dikes often present.

There are many varieties of this class of rocks recognized by petrologists, based on the presence of particular minerals and textures. One of the most important, composed of pyroxene, labradorite feldspar, and iron ore, with a certain textural arrangement of the minerals, is known as *diabase*. The larger part of the great trap sheets of the lower Connecticut valley and of northern New Jersey is composed of diabase.

Peridotites. — These rocks, composed generally of variable mixtures of ferromagnesian minerals, with olivine (peridote) $(MgFe)_2SiO_4$, are not common, and are usually found in minor intrusions, dikes, sheets, small stocks, etc. They are very interesting and important, however, as being the source of ores of chromium, nickel, platinum, and of the diamond. They are generally very dark to black heavy rocks from the large amount of iron-bearing minerals present. A variety composed wholly of olivine is known as *dunite* and in the Carolinas the occurrences of it contain the mineral corundum, Al_2O_3, which is used as an important abrasive in the manufacture of emery wheels, etc. The diamonds of South Africa occur in volcanic necks, or pipes, composed of this rock, and they have been found rather recently in somewhat similar intrusions of it in Arkansas.

Porphyries. — As may be seen by reference to the table of classification there are various kinds of porphyry depending on the coarseness of the ground-mass and its composition, and on the kinds of minerals which may be embedded in it as phenocrysts. Thus we

may have granite-porphyry, syenite-porphyry or felsite-porphyry. Feldspars are the most common phenocrysts, quartz is seen in many occurrences; sometimes dark to black flakes or prisms of mica, hornblende or pyroxene occur. The porphyries are a very common class of rocks, found chiefly in the minor intrusions, in dikes, sheets, and laccoliths, and often in necks; they are not often seen in the great stocks and bathyliths. They are seen also as composing many extrusive lava flows. The intrusions of porphyry in the Rocky Mountains region are very common, and in many cases are accompanied by valuable deposits of gold, silver, lead and other ores where they come in contact with limestone. Examples of this are seen at Leadville and other places in Colorado, Montana, Nevada, etc. Porphyries rarely make good building stones as the masses are generally too much divided by joints, but in places they serve as excellent road material. A porphyry is shown in Fig. 253.

Felsite and Basalt. — Felsite represents the dense lava forms of the intrusive granites, syenites, etc. Pure felsite is not common because generally phenocrysts of feldspar, quartz, and mica are present making felsite-porphyry. The number of these embedded crystals varies within the widest bounds so that there is every transition between felsite and felsite-porphyry. The colors vary from white to gray, red, purple and brown. When the color is very dark gray, dark green, or black the rock is *basalt*, the common effusive of the ferromagnesian magmas and granular rocks, less often seen in dikes, sheets, etc. The effusive occurrences of felsites and basalts have been already treated under volcanoes and eruptions. The enormous tracts of land in western America, in India, etc., flooded by outflows of basalt have been mentioned.

The feldspathic lavas, here called felsites, are subdivided by petrographers into groups based on the nature of the feldspars and other minerals, as shown by microscopical study and chemical analysis. They are as follows:

Chief component minerals	Rock name	Equivalent coarse-grained rock in petrographic classification	Equivalent coarse rock in the classification of this book
Alkalic feldspars and quartz	Rhyolite	Granite	Granite
Lime-soda feldspars and quartz	Dacite	Quartz-diorite	Granite
Alkalic feldspars, little or no quartz	Trachyte	Syenite	Syenite, mostly
Soda-lime feldspars, little or no quartz	Andesite	Diorite	Syenite and Diorite
Alkalic feldspars and nephelite	Phonolite	Nephelite Syenite	Nephelite-Syenite

These terms, rhyolite, andesite, etc., are constantly used by geologists on the basis of study and experience, but the distinction between the varieties cannot be accurately made without such study, and for a general term felsite is used for the group.

Glassy Rocks. — Volcanic glasses occur on the surface of outflows of lava, as thin crusts, or where a lava flow has been very quickly cooled, and they are mostly limited to felsite-magmas. Bright, clean, hard volcanic glass is called *obsidian*, and *pitchstone* when the luster is duller and more pitchy. *Pumice* is a frothy condition of the glass. The spongy, scoriaceous forms seen on lava are apt to be more or less glassy. In past times obsidian was much used by primitive peoples in making weapons, implements, etc. The ancient Mexicans were especially skillful in fashioning knives and razors from it. Natural glasses, like the obsidian of the Yellowstone Park are apt to contain crystallized minerals in rounded forms with radiating structures, known as spherulites, or lining shell-like cavities known as lithophysae (stone bubbles).

CHAPTER XIII

METAMORPHISM AND METAMORPHIC ROCKS

Definition of Metamorphism. — Observation teaches us that in addition to the igneous and sedimentary ones previously described there is a third class of rocks which cannot be directly referred to either, and these have been termed the metamorphic ones. Further, study of them shows that in some places these rocks may be found to pass gradually into those whose fossils and stratification prove them undeniably to be of sedimentary origin, while on the other hand, in other places, they grade into rocks whose characters show no less conclusively that they are of igneous origin. From this we learn that the metamorphic rocks are closely allied to both of the other classes and are, indeed, formed from them by processes it is our purpose to investigate and study. The word *metamorphic* means *changed in form*, and *metamorphism* is used as a general term for all those changes by which the original characters of rocks are more or less completely altered, in that their component kinds of minerals and textures are transformed into other minerals or textures, or both. The change may be so great that the metamorphic product bears no resemblance to the rock from which it was derived, but appears like one of a new kind. Where sedimentary rocks have been thus thoroughly *metamorphosed* they are much harder, denser, more crystalline, and the fossils and, perhaps, even the marks of stratification, have been more or less completely obliterated. As to the igneous rocks the particular features which distinguish them may disappear, and they may assume a banded appearance and cleavage which resemble those of sedimentary kinds.

Thus limestone may pass into highly crystalline marble with consequent loss of color and disappearance of fossils; basalt may be converted into green, slaty rocks which give no hint of their original igneous nature. All stages of transition may be found between such extremes, but under metamorphic rocks we understand that the changes of the original rocks have been so profound that, as stated above, their original characters have been entirely obliterated, or nearly so, and distinctly new kinds of rocks formed. The various changes which rocks undergo from the effects of *weathering*, are, strictly speaking, to be classed as metamorphic ones. But they have been already considered under the work of the atmosphere and the production of soils, and, therefore, these agencies, and the soils and weathered rocks which result from their action, are not considered in this place.

Metamorphic Agencies. — These are mechanical movements of the earth's crust, downward pressure of superincumbent masses, horizontal thrusts, chemical action of liquids and gases and the effect of heat. These may be simplified into the effects of movement, water solutions, and heat, and to produce complete metamorphism in rocks, probably all three of these are required, though not necessarily all to the same extent. For sometimes the effect of one factor, such as heat, may greatly predominate, that of liquids be less marked, and those of pressure or movement be quite negligible. Thus in the metamorphic changes induced in surrounding rocks by the intrusion of a body of molten magma in the form of a neck or stock, heat is, perhaps, the main agent, while pressure is of little or no effect. We will consider the different agencies in detail.

Movement and Pressure. — Simple downward pressure, sometimes called *static pressure*, as exerted in the upper part of the earth's crust by the weight of the overlying layers, appears to have little metamorphic effect on rocks. It must tend to consolidate sediments by bringing the grains together, but many instances are known where strata have been buried for long geologic periods under great thicknesses of overlying beds without having suffered any notable metamorphic change, as may be observed where they have been gently raised and exposed by erosion. On the other hand, it is natural to suppose that the enormous pressure which reigns at greater depths in the shell must be a powerful factor in inducing certain chemical work and effects in rock formation, but we have at present no definite information, or means of learning about them, and our ideas on the subject are mostly in the nature of speculation.

With respect to *movement* it is quite otherwise. The crust of the earth, as we shall see later, has been in many places, at different times, under great compressive force which has found relief by wrinkling up the outer shell into mountain ranges. By this mountain-forming force whole masses of strata, often with included igneous rocks, intrusive and extrusive, are folded, crushed, and mashed together in the most involved and intricate manner. Not only are they subjected to vast pressure, but also in the mashing to enormous shearing stresses, which produce forced differential movements among the rock particles. The *shear* may be characterized as a sliding of the particles past one another so that a slipping of adjacent layers, relative to one another, is produced, while *mashing* is a process of flowage by which adjacent layers become thinner, but do not slide upon one another. It is particularly this mashing and shearing which are of great power in producing metamorphism.

The visible effects may often be seen by the manner in which large crystals, included pebbles, or fossils, are flattened and elongated, in the plane at right angles to the mashing force. It is possible, in fact, for mashing and shearing alone to produce rocks having the characteristic outward metamorphic texture, without change in the original mineral composition, but in combination with heat and water, this is of the highest importance in inducing chemical changes, and the production of new minerals. It is, indeed, noticeable that as long as rocks retain their original position, they may be unaltered, but as we commence to find them disturbed by compressive mountain-making forces, they begin to show signs of metamorphism, and in proportion to the degree to which they have been folded up, mashed, and sheared, they become more and more metamorphosed. The effects produced in this way are commonly referred to as *dynamic-metamorphism*, or *dynamo-metamorphism*.

Heat. — The effect of heat as a metamorphic agent is very strong, as is well seen where intrusive igneous rocks have come in contact with sedimentary ones and metamorphosed them. It increases greatly the solvent action of solutions; it tends to break up the chemical compounds of many minerals, and to thus make new ones. The heat needed for metamorphism may possibly in part be that of the interior of the earth, it may be supplied in part by the transformation of energy resulting from the movements, the folding and crushing of the rock masses, but it is probably mostly due to the intrusion of molten magma, which is apt to rise and be intruded into rock masses when they are uplifted and folded.

Liquids and Gases. — The most important of these is water, which, with heat and pressure, becomes a powerful chemical agent. It acts as a solvent, and helps crystallization, and in the making of new chemical compounds. It is aided in its action by material it may carry in solution, such as alkalies, and by volatile substances coming from the magma intrusions, such as various acid-forming substances, fluorine, for example, as already explained under volcanic action. This explains the presence in metamorphic rocks of minerals, which contain chemically combined the elements of water and other gases, and, as we shall see later, the veins and ore deposits frequently found in them.

Effect of Depth. — The outer shell of the earth may be divided into different zones, according to the various geological activities going on at different levels. They are illustrated in the diagram shown in Fig. 255. Below the upper layer of soil the bed-rock is full of fractures and as far down as the surface of ground water it is ex-

posed to atmospheric agencies, the moisture, carbonic acid, etc., which tend to cause decay and convert the rocks into soil. It is a zone of rock destruction, as previously shown in the first chapter and may be called the *belt of weathering* (*a*), Fig. 255.

Below this belt comes the zone (*b*) in which the rocks are full of cavities and fractures filled with water. The upper limit is that of the surface of ground water, the lower that where openings cease, as described in the next zone. It may be called the *zone of fracture*, if we disregard the upper limit. In this the action of water is most important, it performs chemical work, aided by the carbonic and other acids it may carry. The tendency is for the silicate minerals of the rocks to change into those containing water in combination, or into carbonates. Substances are taken into solution, and, added to by those leached downward from the belt of weathering, are deposited in the fissures and pores of the rocks. From this cementing and filling of cavities it may be termed the *belt of cementation*.

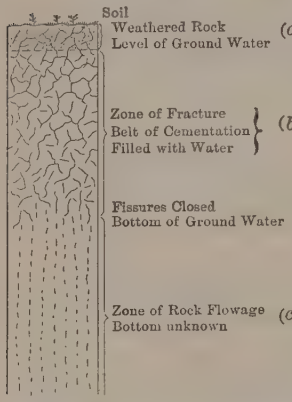


Fig. 255. — Diagram to illustrate different zones in the Earth's outer shell.

Below this comes the zone (*c*), Fig. 255, where the pressure of the superincumbent masses is greater than the elastic limit of the strength of rocks; they crush under it and are to be regarded as being in a relatively plastic condition. As a result all openings and fractures are closed and this must mark the limit downward of the percolation of ground water. The upper limit of this zone is variable and depends on geological conditions; in times of quiet it may be 15 miles below the surface; in times of compression and mountain-making it may be at a much lesser depth. Where its lower level may be we do not know. In this zone the enormous pressure and increasing heat of the earth are the chief agencies; liquids and gases are less important and tend to be squeezed out; thus carbonates change to silicates and CO_2 is expelled. The new mineral compounds must tend to be of smaller volume and higher specific gravity from condensation. This zone of rock flowage we may term the zone of *constructive metamorphism*.

It is chiefly in the lower part of the belt of cementation, or zone of fracture, and in the upper part of the zone of rock flowage that the work of producing metamorphic rocks, as we know them, is done.

The zone of rock fracture has been called the zone of *katamorphism* and that of rock flowage the zone of *anamorphism* by Van Hise; the meaning of these terms is that one is a downward change, or breaking up into simpler compounds, while the latter is an upward change or reconstruction into more complex compounds, or minerals. These terms are frequently used by geologists in referring to metamorphism and metamorphic rocks.

Regional and Contact Metamorphism. — It should be stated before proceeding further that for practical purposes two varieties or effects of metamorphism are recognized by geologists. In the first the rocks are changed or metamorphosed over extensive regions; all the different factors of metamorphism have worked upon them; but pressure, with mashing and shearing, has been especially important, and as a result the rocks are apt to have a peculiar texture which distinguishes them and which will be presently described. In recognition of the wide extent to which rocks may thus be changed this has been called *regional metamorphism*, and sometimes general metamorphism, and the dynamic metamorphism referred to previously is merely a pronounced phase of it in one direction.

But, on the other hand, rocks, especially sedimentary ones, may be metamorphosed by the heat, liquids, and gases issuing from intrusive molten magmas which may come in contact with them. Here it is evident that mashing and shearing are unimportant; the rocks are wanting in the characteristic texture mentioned above and described beyond, but may yet be thoroughly changed; thus chalk may be altered to marble. With reference to the fact that metamorphism produced in this manner is confined to the immediate neighborhood of the igneous rocks which have produced it and, therefore, compared with regional metamorphism, is limited in extent, it is known as *local*, or more commonly *contact metamorphism*. We will go on with the consideration of regional metamorphism and contact metamorphism will be treated at the end of this chapter.

Minerals of Metamorphic Rocks. — The chemical compounds which form the minerals found in the rocks vary greatly in their ability to withstand the changes of conditions which different geological processes subject them to. With new chemical and physical factors operating upon them they will tend to change into new minerals, or those chemical combinations which will be the most stable under the new conditions. Thus we see feldspar alter into clay and other substances through the action of water and carbon dioxide, as explained under soils, page 24. The igneous rocks are characterized by one set of minerals, chiefly silicates, while carbonates and hydrated oxides and silicates are mostly found in the sedimentary ones. Some minerals like quartz have a wide range of stability and are found in all three classes of rocks, but many others when subjected to metamorphic processes are converted into others; thus carbonates are apt to be changed into silicates. Quartz, the feldspars, mica and hornblende are found in

both igneous and metamorphic rocks, while common garnet, staurolite, cyanite, talc, chlorite and serpentine are common minerals of metamorphic ones.

Texture. — Most metamorphic rocks resemble the igneous ones in that they are highly crystalline, but they differ from them in possessing a parallel structure which may at times closely resemble stratification. This parallel structure expresses itself to a variable extent by a foliated, laminated, or as it is often termed, a *schistose* texture, and a rock possessing it is known as a *schist*. By reason of it a rock tends to split, or cleave, more or less perfectly in the direction of a plane passing through it which we may call the plane of cleavage. While it is the characteristic texture of metamorphic rocks, which for this reason have been sometimes called the *crystalline schists*, there are a few, such as serpentine, marble and quartzite, which may not show any trace of this parallel schistose structure and cleavage. In some cases the parallel structure is straight, or nearly so, as seen in Fig. 256, for considerable distances; often, however, the banding is very much contorted, bent, or curled, showing the amount of mashing and kneading the original rocks were subjected to. See Fig. 259.

Observation shows that the schistose texture is due to the arrangement of unlike mineral grains in layers or flattened lenses, or to parallel grouping of prismatic or tabular minerals, such as hornblende or mica, or to a combination of both. It is a result of the granulation and recrystallization to which the original rocks were subjected and has been imposed upon igneous and sedimentary rocks alike. The resemblance of the banded, laminated appearance of schistose metamorphic rocks to stratification led in the past to the erroneous view that they were wholly derived from stratified ones; that they could also be made from igneous rocks was learned much later.

Cleavage. — The cleavage which is exhibited by schistose metamorphic rocks is most perfectly developed in slates, so much so that this variety of it is often spoken of as *slaty cleavage*. Slates used for roofing, blackboards and other purposes are examples of this. Its origin has been the cause of much speculation and the subject of investigation, along both experimental and mathematical, as well as geological, lines. From this it has become clear that it is the result of great pressure upon the material and that *the planes of cleavage are at right angles to the direction of pressure*. When fine-grained sediments, muds and clays, are subjected to intense pressure oblong particles tend to rotate so that their lengths are perpendicular to the direction of pressure; they also tend to become flattened perpendicularly to it. More important is the fact that many of the elongate or flattened minerals, such as mica, kaolin, chlorite and

Fig. 256. — Banded gneiss, Portland Township, Ottawa Co., Quebec.
M. E. Wilson; Geol. Surv. of Canada.

hornblende, have an excellent cleavage parallel to the long or flat directions. All these features tend to give the rock a capacity to cleave readily in one direction. Slaty cleavage is thus partly molecular, when it passes through a single mineral particle, and partly mechanical, when it passes between arranged or unlike particles. A considerable part of the minerals may not be original, such as the micas, but formed by the metamorphism accompanying the pressure.

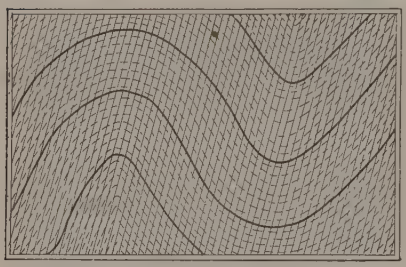


Fig. 257. — Slaty cleavage in folded beds.

The cleavage planes do not necessarily bear any definite relation to those of original bedding. The beds were laid down in horizontal position and the direction of pressure is also horizontal, or nearly so; the cleavage planes being at right angles to this may cut the bedding at right, or

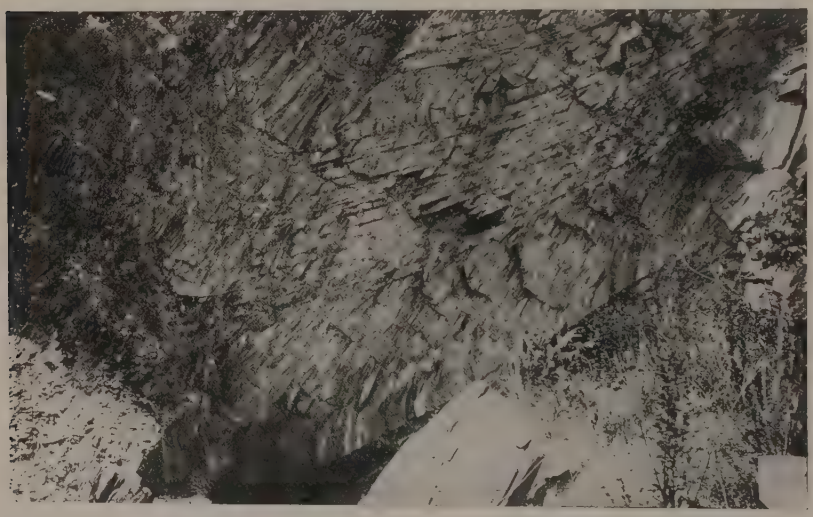


Fig. 258. — Slaty cleavage cutting at a high angle, beds folded in a syncline. Slatington, Penna. E. B. Hardin, U. S. Geol. Surv.

highly inclined angles. But as the beds may be folded before the pressure becomes intense, the cleavages may pass through the bedding at various angles, though they themselves are strictly parallel, see Fig. 257, while a view of the same thing is seen in Fig. 258.

While by far the greater number of slates have been made from original fine sediments, muds and clays, slaty rocks have been produced by the mashing of fine-grained igneous rocks also, such as felsites and basalts and beds of volcanic ash. In this process original characteristic features in the rocks may become greatly distorted and even obliterated; thus fossils and pebbles in the stratified rocks and embedded crystals and other structures of the igneous ones may be flattened into lenses or squeezed out into cylinders. And it must also be remembered that what has been here said of cleavage in slates is also true of other schistose rocks in which it differs only in the degree of being less perfectly developed.

At times cleavage may be mistaken for original bedding, unless care is taken, and wrong interpretations of geological structure obtained. It is sometimes important to indicate it on geologic maps and this may be done by observing its dip and strike, like that of a bedding plane. The important relation it bears to mountain ranges and their origin will be discussed under that subject.

Places of Occurrence. — Metamorphic rocks are widely distributed over the earth's surface and in some regions they are the only kind exposed over extensive areas. This is true in eastern Canada, where, in places, considerable bodies of intrusive igneous rocks are associated with them. They are found quite generally in New England, in the Adirondacks and in a strip of country running from northern New Jersey to Georgia. Other occurrences will be mentioned in the second part of this work. There is reason also for thinking that over the continental areas they must form the basement upon which all the later unmetamorphosed stratified rocks rest. For wherever these latter are sufficiently cut away by erosion this metamorphic basement appears, except where it has been cut into by intrusion of stocks and bathyliths of granite and other igneous rocks. The metamorphic rocks also form the interior core of many mountain ranges, and have been exposed by erosion. These mountain ranges, as will be discussed later, have been made by folding of the strata, and in proportion to the intricacy of the folding and mashing so is the degree of metamorphism of the rocks increased.

The relations between folding, elevation, and metamorphism is so well established that where we find rocks intricately folded and very metamorphic we assume that an elevation once existed but has been eroded away, or, in general, that metamorphic rocks can only be exposed at the surface after continued erosion. Following out this idea metamorphic rocks are sometimes spoken of as *continental* rocks, because they imply (when originally of stratified kinds) continued erosion of land masses; laying down of beds of sediments; and folding and crushing of the latter to give metamorphism with incidental production of mountain ranges; and lastly erosion again to expose the metamorphic rocks. Such an array of processes could occur only on a great scale and therefore on and about continental masses; consequently when metamorphic rocks are found in place on Fiji, New Caledonia, South Georgia and other islands, it is held that this proves that these are mere remnants from the wrecks of former continents.

Age of Metamorphic Rocks. — Some of these facts, previously mentioned, led to the view that, from the geological standpoint, metamorphic rocks must be very old. This by no means necessarily follows, nor is it always true. For while we find unmodified beds of quite early geologic age in Russia and in the upper Mississippi valley, which have not been changed from their original horizontal position, on the other hand, strata of a comparatively recent period which have been greatly folded up in the Alps, the Coast Range and in some other mountains have been strongly metamorphosed. It merely depends on whether they have been subjected to metamorphic processes or not, and the older the rocks are, the more likely they are to have suffered from them. Time, however, is one of the most important factors in metamorphism, and, even where relatively recent strata have been changed and then exposed, the time involved, from our standpoint, is immensely long.

The Metamorphic Rocks

Introductory. — Since the metamorphic rocks are made from both stratified and igneous ones, and there are almost infinite varieties of both of these, it follows that there must be a very great number of different kinds of metamorphic products. Yet in the same way that we were able for ordinary purposes to gather the igneous and stratified rocks into a small number of groups, so we can consider the metamorphic ones under the few most important types.

The sedimentary rocks are very largely made of the disintegrated igneous ones. In the process of breaking down and disintegration it may happen that there is not much weathering and chemical change. In this case the sedimentary rock will not differ very greatly from the original igneous one in chemical and mineral composition. Thus the red-brown sandstone (arkose) of the Connecticut Valley, which is full of feldspar, has practically the same composition as the masses of granite of the adjacent region. If such arkoses are so thoroughly metamorphosed as to lose their original characters it is evident that we could not distinguish them from the metamorphosed granites, or say what their former status was. From this it will be clear that, while in some cases we can tell the origin of a metamorphic rock at once, as in marble and quartzite, and in others after careful study in the field and laboratory, in many cases we are unable to determine from what they were derived.

Classification. — Remembering the simple classification of the sedimentary rocks previously given, it is possible, in a general way,

to show the relation between the most common ones and their metamorphic derivatives in the following table:

Sediments	Compacted strata	Metamorphic rocks
Gravel	Conglomerate	Gneiss, and various schists
Sand	Sandstone	Quartzite, and various schists
Silt and clay	Shale	Slate, and various schists
Lime deposits	Limestone	Marble, and various schists

In the case of the igneous rocks, recalling that they may be roughly divided into two main groups, the one chiefly composed of light-colored feldspathic minerals, and the other mostly of dark ferromagnesian ones, we can illustrate also, in a very rough and general way, the relation between them and their metamorphic derivatives in the following table:

Igneous rocks	Metamorphic rocks
Coarse-grained feldspathic types, such as *granites*, etc	*Gneiss*
Fine-grained feldspathic types, such as *felsite*, *tuffs*, etc	*Slate* and *Schists*.
Ferromagnesian rocks, such as *dolerites* and *basalt*	*Hornblende-Schists*, various schists, and *Serpentine*.

Comparison of the tables will show that gneisses and schists may have diverse origins, as previously pointed out. Combining the results of these tables, we may obtain the following main groups of metamorphic rocks, distinguished according to their mineral composition, or by their texture, or by a combination of both.

Grouping of Metamorphic Rocks

1. *Gneisses*, rocks containing feldspar.
2. *Mica-schist* and *quartzite*.
3. *Slates* and phyllites.
4. *Hornblende schist;* talc-, and chlorite-schists.
5. *Marble*, dolomite, mixed carbonate-silicate rocks.
6. Serpentine. Iron ores.

Gneiss. — The common varieties of this rock (pronounced nice) consist, like granite, of quartz, feldspar, and mica, but in gneiss the mica is arranged in more or less definite planes and the rock has thus a rude cleavage. Sometimes hornblende may accompany or

replace the mica, and other minerals, such as garnet, may also occur, giving different varieties. All degrees of transition between granite and gneiss are very common, and in other cases, where gneisses were made from conglomerates, the original pebbles may still show as lenticular masses. Gneiss is one of the most common of metamorphic rocks and it appears also as, perhaps, the most deeply situated of any known rock, formed, probably, in the deepest zones of metamorphism. Some rocks are spoken of as granite-gneisses and it seems probable that in some cases the gneissoid texture has been assumed, through mashing and shearing, by magmas while still in a

Fig. 259. — Contorted gneiss; Fullerton, Hudson Bay, Canada. A. P. Low. Geol. Surv. of Canada.

pasty, viscous condition. A view of beds of gneiss is seen in Fig. 259.

Mica Schist and Quartzite. — When a sandstone becomes so firmly cemented by deposit of silica that the fracture takes place through the grains of quartz sand, instead of around them, it has become a *quartzite*. In this condition it shows no schistose structure, but is massive. If subjected to mashing a quartz schist may be formed, or, if it is an impure sandstone, mica is liable to develop and may increase in amount until it appears the most prominent ingredient, and the rock becomes *mica-schist*. All degrees of transition between gneisses, quartzites and mica-schists may be found, depending on the relative quantities of quartz, feldspar and mica. Quartzites are usually massive rocks of light colors, white, gray,

reddish, or buff, and of hard flinty aspect. Mica-schist is a very schistose, often friable rock, usually of a silvery luster and often dotted with common red garnets.

Slates. — The origin of these rocks from fine-grained sediments such as muds, clays and ash deposits by the action of compressive forces has been already discussed. While they may have various colors, red, green, gray, etc., the most common one is dark gray to black, due to carbonaceous material from organic matter in the original muds. They are closely related to shales, but the distinction between them is that such cleavage or lamination as a shale may possess is due to original bedding planes; while in slates it is a

Fig. 260. — Illustrates the occurrence of slates and cleavage. Slate quarries. Brownsville, Me. T. N. Dale, U. S. Geol. Surv.

secondary induced phenomenon, which, as previously stated, may bear no relation to bedding, Fig. 260. Slate is sometimes called *argillite* in reference to its origin from clay (Greek, argilos, clay).

Phyllites. — These are rocks resembling slates, but having a larger proportion of mica, which gives them a silky, glimmering luster. They are transitional between slate and mica-schist. The name which means "leaf stone" has been given for the remarkable cleavage, or fissile character, of these rocks. They appear in some cases to have been formed, like the ordinary slates, from sediments, but to be more highly metamorphic and recrystallized. In other instances they have been made from igneous material, felsite lavas, tuffs, etc., by mashing, shearing and accompanying agencies of metamorphism. They have sometimes been called "hydro-mica-schist" in America.

Schists: Hornblende-Schist. — There is a great variety of rocks depending on the different minerals which compose them, which have a more or less pronounced foliated or schistose structure. Schist, as previously mentioned, is a general name for the group, and *hornblende-schist* may be taken as a most common and typical representative. The rock is generally dark green to black, and the parallel prisms of hornblende, if not too large, generally give it a silky luster. The rock-cleavage is almost slaty in some cases. Talc-schist and chlorite-schist are other common varieties in which talc and chlorite are predominant minerals.

Marble. — This is the metamorphic condition of the sedimentary rocks formed by lime deposits, such as limestone and chalk. Generally the marks of bedding, fossils, etc., are effaced and the material converted into crystalline grains of calcite. It is, therefore, harder, more compact, with purer colors, and takes a good polish. Just as there are ordinary limestones consisting only of carbonate of lime, and dolomitic limestones containing magnesium carbonate, $MgCO_3$, in variable quantity in addition to the $CaCO_3$, so we have *lime* marbles and *dolomite* marbles. Commercially, as marble is used, this chemical difference is not a matter of importance, but geologically, it is of interest because the kinds of minerals that are liable to be associated with the marbles, or to be found, in some cases, scattered more or less thickly through them, are quite different in the two kinds. Marble is generally massive and shows no cleavage, even when found in regions where its association with schists shows it must have been subjected to enormous mashing and shearing stresses. The reason for this appears to be that the mineral calcite has a curious property of being able to permit of motion of its molecules in certain directions without the crystals being destroyed. It is somewhat analogous to what was described of ice, page 122. Owing to this the stresses are absorbed molecularly and no arrangements of the grains are produced which show as foliation in the outward structure.

Pure marble is white, the mottling, banding and colors shown by ornamental varieties being due to impurities, the red and yellow tones to oxides of iron, the grays and blacks to varying proportions of organic matter. Besides being produced by regional, marble is also formed by contact metamorphism.

Serpentine. — This name is given to a mineral, a hydrous silicate of magnesia, $H_4Mg_3Si_2O_9$, and also to a rock largely or entirely composed of it. The rock is usually greenish to black, soft, of a greasy feel and massive, or without cleavage. Some of the blotched, lighter green varieties are used as building and ornamental stones. Most serpentines appear to have been made by hydrothermal metamorphism (action of hot waters) on deeply buried masses of igneous rock rich in magnesia, such as peridotite for example, whereby the magnesium silicates change

to this hydrated variety. Impure dolomite marbles may contain magnesium silicates, olivine, pyroxene, etc., which may alter to serpentine. 'Verde antique' appears in some cases to be a mixture of marble and serpentine of this nature.

Iron Ore. — The mode in which beds of iron ore may be accumulated in the stratified rocks has been already described. Such iron ores may be subjected to metamorphic processes like other rocks, and as a result the loose earthy materials may be changed to hard crystalline rocks; thus beds of limonite and clay-ironstone may be altered to hematite and magnetite.

Anthracite, or hard coal, is regarded by many as the metamorphic equivalent of bituminous, or soft coal. The degree of metamorphism is, however, very slight; were coal changed in proportion as the other metamorphic rocks we have described, it would be converted, not into anthracite, but into graphite, which is not combustible in the air under ordinary conditions.

Contact Metamorphism

Introductory. — As previously explained, this term is used to denote the changes which are induced in already existent rocks by the intrusion into them of a mass of molten magma, and also of the effect of the contact on the igneous rock which the magma itself forms in cooling. We may thus observe it from two standpoints; that of the result on the igneous rock-body, termed the *endomorphic* effect, and that of the action on the enclosing rocks, or the *exomorphic* one. Unlike their importance in regional metamorphism, mashing and crushing are generally negligible factors, and heat and the action of vapors and liquids are the chief agents in producing the changes observed. Therefore, in the changed rock, while new minerals may be formed, and it may have a harder, denser, more crystalline texture than the normal rock of the region, it very rarely shows the schistose, or cleavable structure as a result. The new rocks are massive and not schists, except as they may retain this structure from their previous condition.

Endomorphic Effect. — In the igneous rock-body itself two effects may be noticed as one approaches the contact. The first and most usual is a change in the *texture* of the intruding rock. It grows much *finer in grain* and at the contact wall may be very dense; thus a granite may change to a felsite. The reason for this is the quicker crystallization and solidification induced in the magma by the chill of the cold rock-wall with which it comes in contact, as explained under igneous rocks, page 306. Sometimes the igneous rock is not only denser but changes from an evenly granular to a *porphyritic texture* at the contact; which is also indicative of more rapid cooling. Sometimes no change of grain is visible and, in this case, we must assume that the rock-wall was thoroughly heated by the flow of magma past it, as in a volcanic conduit for example, be-

fore the final charge of magma came to rest against it. In such circumstances, the magma would not be quickly chilled and no special change in grain might be expected. But in this case the exomorphic effects are usually much more marked.

The other effect is that sometimes new minerals, other than the normal ones of the igneous rock may be found occurring at, or near, the contact. Thus, for example, tourmaline may be seen not infrequently in masses of granite. The origin of such minerals is due to the chemical effect of the vapors and gases of the magma, which tend to be excluded as the mass cools and crystallizes, and to escape to the margin, and into the surrounding rocks.

Exomorphic Effects. — The most noticeable evidence of the exterior effect of contact metamorphism is a baking, hardening, or toughening of the surrounding rocks. As a result it not infrequently happens that they resist erosion better than the intruded igneous mass, or the unchanged country rocks, and form projecting topographic forms; such as ridges, peaks, etc. In the case of dikes, it may happen that both the dikes and the sedimentary beds penetrated by them are lowered more rapidly by erosion than the hardened contact rock on either side leaving it standing up in parallel walls. In most cases, however, the resistance to erosion is very similar to that of the igneous rocks.

The breadth of the zone depends largely on the size of the igneous intrusion; the widest and most pronounced ones being found about the great stocks and bathyliths. Around them it has been found in

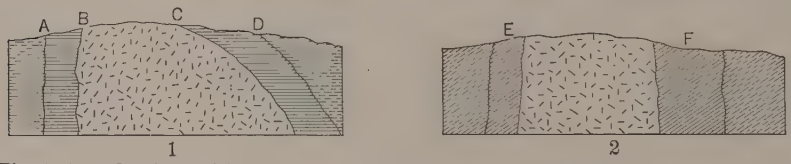


Fig. 261. — Sections of intruded stocks and their contact zones. In 1, the breadth on the surface *CD* is greater than *AB*, depending on shape of igneous mass. In 2, the width *F* is greater than in *E*, depending on inclination of beds.

many places that the contact zone may reach a breadth of a mile, or even more; usually it is some hundreds of yards and, with a small intrusion such as a dike, it may be only a few feet. In extrusive lava flows a small amount of baking of the soils or rocks on which they rest is often noticed.

Relation to Rock Structure. — Around an intrusion it is frequently observed that the width of the contact zone is variable; this may depend very much on the position of the rocks. Thus in Fig. 261, section 1, the sloping inclination of the contact wall pro-

duces a wide zone at *CD*, compared with that of the vertical wall at *AB*. And in section 2 the beds at *F*, sloping into the igneous rock, tend to have their bedding planes opened and to furnish an easy entrance to the vapors and solutions from the cooling magma. Since these vapors and solutions are the chief agents in carrying the heat and producing the metamorphism, it is clear that a broad zone *F* will be made on this side, compared with *E*, where reverse conditions are present and a narrower zone must be formed.

Results on the Different Kinds of Rocks. — The extent to which contact metamorphism produces its effects upon already existent rocks depends very much, in addition to what has been said above, upon the kinds of rocks. It should not be forgotten in this connection that intrusions of igneous rock, such as dikes, may take place into older igneous rocks, as well as into sedimentary ones. The latter, as a rule, are much more profoundly affected than the igneous rocks. For our purpose here they may be divided into the three groups, the *sandstones*, the *shales* (and clays) and the *lime* rocks. On pure sandstones the effect is rather small, though near the contact they may be found changed into quartzite. The lime rocks are changed into marble, of greater or less purity, the masses of which may extend for considerable distances. In the case of clays and shale beds the most notable and, generally, far-reaching results are seen, the soft shales being greatly hardened and, finally, at the contact converted into dense crystalline rock known as hornfels, which in its outward appearance may strongly resemble an igneous rock, such as basalt. The igneous rocks, being the products of fusion, are generally but little affected by later intrusions, especially feldspathic ones, like granite.

In approaching a contact zone in shales, after a slight hardening, one of the most noticeable effects is the production of spots, or knots, in the rock. These may consist of small points, or lumps, or the production of prisms of some mineral, such as andalusite (Al_2SiO_5), which may be black from included carbonaceous matter. Still nearer to the contact, and at it, the knots disappear and the rock has a granular crystalline appearance, which recalls an igneous one.

The most interesting results are produced in limestones, especially impure, cherty ones. Not only are they turned into marble, but a great variety of new minerals may be formed in them, depending on reactions between the bases and acidic oxides present, especially lime and silica. Thus the silica tends to drive out carbon dioxide,

$$CaCO_3 + SiO_2 = CaSiO_3 + CO_2$$

and calcite is changed into lime silicate (wollastonite). If the limestone is dolomite then magnesia takes part

$$(CaMg)CO_3 + SiO_2 = CaMgSiO_3 + CO_2$$

and calcite is changed into pyroxene, and carbon dioxide liberated. Clay may be present, furnishing alumina, and iron oxides may also occur; while, in addition to the water vapor, sulphur, fluorine, boron and other acid-forming elements from the magma, may take part, and thus by various combinations, numbers of new chemical compounds, or minerals, are formed. These more complex reactions may be illustrated by the following one,

Calcite	+ Clay	+ Quartz	= Garnet	+ Carb. dioxide	+ Water.
$3\,CaCO_3$	$+ H_4Al_2Si_2O_9$	$+ SiO_2$	$= Ca_3Al_2Si_3O_{12}$	$+ 3\,CO_2$	$+ 2\,H_2O.$

Thus a limestone, impure with clay and sand, may be changed into garnet with evolution of carbon dioxide and water.

It seems quite certain that, in addition to the water and other volatile substances, silica is carried in solution into the enclosing rocks, taking part in the chemical reactions mentioned above, cementing them by deposit in their pores, as when sandstone is converted into quartzite, and forming veins of quartz in crevices and fissures. The alkalies, soda and potash, are also carried by these solutions, or emanations, from the magmas into the surrounding rocks, and by many geologists it is also claimed that alumina, iron, magnesia, and many other elements are thus transferred in contact metamorphism. It seems probable that in many cases this is to some extent true, but as yet the necessary chemical knowledge, which would permit us to make definite statements, has not been obtained. The importance of these assumptions we shall see when ore deposits are studied.

CHAPTER XIV

THE FRACTURES AND FAULTING OF ROCKS

Fractures; Joints

General Remarks. — The fact that in the outer shell of the earth the rocks are traversed in all directions by fractures, varying from minute crevices to important fissures, has been already alluded to in many parts of this book. We have seen their importance in the weathering of rocks and formation of soil; in the holding and in the circulation of underground water; in earthquakes, and in some metamorphic processes, and we shall meet them again in considering mineral veins. They are, indeed, of great geologic importance, both on account of the processes which give rise to them and from the results which are achieved by their aid. It is fitting, then, that we should study them in some detail.

Fractures are found in all classes of rocks and for purposes of study they may be divided into *joints* and *fissures;* the difference between them is partly one of degree, the joints being developed in a single rock-mass or a certain set of strata, while the great fissures may traverse many adjoining rock masses and may extend to great distances, and partly in the amount of displacement, the joints showing little or no displacement of their contiguous walls, while the greater fissures are revealed to us by differential movements on the opposite sides, as explained later under faults. We will consider the joints first.

Joints in Stratified Rocks. — The smaller fractures which divide the rock masses are those which we may call joints. Examination generally shows that they are present in systems; that is they run as divisional planes through the strata more or less perfectly parallel to definite directions. Often it happens that these directions of jointing are two, vertical, or nearly so, and approximately at right angles and this, combined with the natural divisional bedding planes, divides the strata in series of closely fitted blocks. Or there may be three or more systems of jointing. The finer the grain of the rock, as a rule, the more perfect the jointing. Thus, in shale beds and in limestones, it may be very perfect as illustrated in Fig. 262. Such jointing may arise through various agencies, such as the tension

produced in the beds of sediments by the contraction which ensues when they are elevated from the sea-bottom to form land surfaces and undergo a drying-out process. Or, at such times, or later, the beds may be subjected to folding, warping and torsional effects through crustal movements, by which the joints are made by crack-

Fig. 262. — View illustrating joints in limestone beds. Drummond Is., Mich. I. C. Russell, U. S. Geol. Surv.

ing in regular systems. It has also been suggested that the passage of earthquake waves through the rocks, with the sudden alternate compresssion and tension, is the cause of much of the minor jointing observed. The exact cause of most of the joints is not known, but they have sometimes been classified as tensional or compressional joints according to the supposed nature of the force producing them.

Joints are a matter of great importance in all quarrying, tunneling and mining operations where rock-work enters as an important factor, since the jointing obviously greatly facilitates progress. Otherwise, every rock fragment would have to be broken or blasted loose from bedrock.

In regions where the stratified rocks have been definitely folded, the joints are sometimes the result of *tension* in the anticlines and sometimes of *compression* in the folding. Slaty cleavage is thus commonly found to be associated with joints. In folded strata, when parallel with the strike of the beds, or nearly so, they are called *strike-joints;* when at right angles to this, or nearly so, they are called *dip-joints,* being in line with the dip.

It is often noticed that joints of a certain system in disturbed strata, which are probably to be associated with the folding, extend for long distances, through a whole series of beds, and are known as *master-joints.* They are contrasted with the minor joints which may be limited to a single stratum.

Joints in Igneous Rocks. — The jointing observed in igneous rocks is mostly due to the contraction resulting from the cooling of the heated mass. It occurs just after the solidification from the molten state, when the loss of heat from the newly-formed solid is greatest. It may manifest itself in one of several ways, depending on the rate of cooling, the size and shape of the igneous body, and other things. Thus intrusive masses of granite and other rocks are cut by jointing planes in various directions which divide them into large blocks, often roughly tabular, or into prisms. In some cases, especially in the finer-grained felsites and porphyries, the jointing in sheets, laccoliths and dikes is on a very small scale, well shown in the talus coming from exposures of the igneous rock which consists of small angular fragments. Sometimes in laccoliths, and similar dome-shaped intrusions, there is a shelly jointing on a large scale, parallel to the domed surface. This appears to have been caused by the planes of cooling (and parting) having descended evenly into the mass from the domed surface.

A much rarer kind of jointing seen in igneous rocks is one in which the contraction took place very regularly around certain centers producing spherical masses by the cracking. This kind of structure is especially brought out by the weathering of the rock mass. It occurs in both intrusive bodies and in lava flows. Igneous rock masses may also exhibit jointing, due as in other kinds of rocks, to tensional and compressive stresses in the earth's crust. But as they are previously jointed by contractional cooling, as explained above, this is of minor importance since the stresses are more likely to relieve themselves by movement along the existent joints than by forming new ones.

Columnar Structure. — The most striking method of jointing in an igneous rock, by contraction on cooling, is shown when columnar structure is developed. This takes place in general when the extension of the mass is great in two directions and much less in a third, as in a dike, an intrusive sheet, or a lava flow. The rock-body is then composed of a series of closely fitted prisms which are again divided by cross joints. The prisms may have a variable number of sides, but most commonly they are hexagonal, and sometimes of wonderful regularity of form. They may be several inches or a number of feet in diameter, and from one foot to 200, or even more, in length. See Fig. 263. The Giant's Causeway on the north coast of Ireland is one of the most celebrated examples of this columnar structure. The columns are always perpendicular to the plane of greatest extension of the rock mass, that is to the chief cooling surface, and thus in a level intruded sheet, or in a flow of lava, they stand vertically, while in a dike they tend to be horizontal. Thus

some dikes, exposed as walls by erosion, resemble regularly piled cordwood.

The cause for this structure appears to be this. When the igneous mass is cooling slowly and regularly, centers of cracking tend to occur on the cooling surface at equally spaced intervals. From each interspace three cracks will form

Fig. 263. — 'Devils' Post-pile;' columnar jointing in lava. Head of the San Joaquin River, Cal. H. W. Turner, U. S. Geol. Surv.

and radiate outward at angles of 120°. These, intersecting, produce regular hexagons and the cracks penetrating inward make the columns. But as the contractional centers are not always equally spaced, four, five and even seven-sided columns occur. The columns again, contracting lengthwise, break into sections. The same principle is seen in the manner in which drying mud-flats crack into polygonal shapes. See Fig. 210.

Jointing in Metamorphic Rocks. — The jointing seen in these rocks depends largely on their nature. In the massive gneisses it is very much like that in granite, while in the very fissile and schistose rocks, such as slates for example, it is more like that observed in many sedimentary beds. In general it may be said to resemble that in the sedimentaries, but to be less perfect; as a rule the metamorphic rocks are apt to be much jointed.

Great Fissures. — In addition to the divisional planes in the rocks, which have been described above as joints, they are penetrated by fissures on a great, and in some cases vast, scale. The most direct evidence of these great fissures is seen in the phenomena of faults, as described later, but the indirect evidence of their existence is also shown in a number of ways. Thus, the alignment of

volcanoes in many places suggests it (page 204); the arrangements of drainage in some places, and the direction of mountain ranges in others, also leads us to infer their existence. The outer crust of the earth appears, indeed, to be everywhere divided into great blocks by these fissures. Usually the walls of the fissures are pressed tightly together, in many cases they are healed by deposits of mineral matter in them. In a few instances they would be open save for the débris which has tumbled into them, or been broken from their walls, and which fills them up. Any further discussion of them leads us inevitably to the subject of faults.

Faulting

Faults. — When fissures have been formed in the rock masses of the outer shell of the earth, movements along the face of such fissures may occur at the time of their formation, or subsequently, giving rise to displacements of the rock masses, compared with their former positions. Such displacements are called *faults*, and faults are a matter of great importance in geology. We have already met them in discussing movements of the earth's crust and earthquakes, and we shall observe them playing very important parts in our consideration of mountain ranges and of ore deposits. They are a more or less constantly recurring feature which must be dealt with in the proper understanding and delineation of geologic structures. As geologic phenomena they are, therefore, of interest, not only from the scientific, but also from economic and technical standpoints.

Faults are frequently described and treated as if they were connected only with the stratified rocks. This is a mistake, for while they are most easily observed in such rocks, and thus, perhaps, seem to occur most often in them, they are also found in igneous and metamorphic ones and may give rise in them to important structures and be of great technical consequence.

The Fault-surface. — The fissure along which movement and dislocation has occurred is often spoken of as the fault plane. While it is, perhaps, natural to speak of it as a plane, it is probably rarely flat for any distance, but more or less warped, broken, and frequently offset, and it is, therefore, better and causes less misapprehension to term it the *fault-surface*. Moreover, the movement in faulting may occur, not upon one determined surface, but upon a number of more or less closely adjacent ones producing a fault zone, in which the various slipped blocks may make in the aggregate the total displacement. Such a distribution is sometimes called step-faulting. The masses of rock involved in fault movements are generally of such size and weight, and often so compressed together, that the

motion of one fault face on the other, along the faulting surface, takes place under tremendous pressure. As a result of this rubbing under pressure, the rock faces are smoothed and striated and not infrequently beautifully polished, and such polishings and groovings are known as *slickensides*. The line of intersection of the fault with the plane of the horizon is called the *strike*, or trend, of the fault, just as we speak of the strike of the bedding plane of upturned sediments (page 282). The surface of faulting is rarely exactly vertical, it is apt to be inclined and, in some cases, so much so that it may approach horizontality. The angle of incidence between the fault-surface and the vertical plane passed through the line of strike is the *hade* (see page 296); the angle with the plane of the horizon is the *dip*, as with strata, and this is the complement to the hade. As it is more natural to think of fissures with reference to vertical directions, hade is used, possibly, more conveniently, though perhaps less commonly, than dip. In the case of an inclined fault the side which tends to be above is known as the *hanging wall*, the other as the *foot-wall*. See Fig. 264. If one were to imagine the fissure opened and one descending it, the appropriateness of these old mining terms becomes obvious.

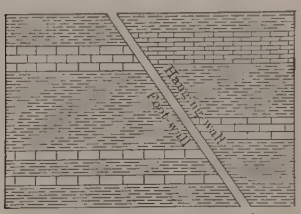


Fig. 264. — Diagram to show fault terms.

A fault is not infrequently composed of numerous parallel fissures and slips. While the fissure is generally tightly closed it may, on occasion, have opened and been filled with fragments from above, or the grinding of the walls upon one another may produce a zone of broken material, and such angular, crushed rock filling a fault is known as *fault-breccia*. Examination often shows also that when stratified beds are faulted, as shown in Fig. 265, there is a curvature of them at the fault surface resulting from the drag. Such curvature, as illustrated, may be a useful aid in determining the directions of motion on the opposite sides.

Motion on the Fault-surface. — Experience shows that if we consider one side of a fault to stand fast, motion on the other side may be up, down, side-wise, or obliquely. Thus in Fig. 266 the lettered plane may represent the fault face, which for convenience we may consider to remain at rest, the other side which undergoes motion having been removed to expose it. If we suppose some particle A, for instance a pebble, to be cleft by the fault-fissure, then one part A remains in its original place and the other part B, embedded in the other face, may be carried in some direction by the faulting. This line A–B is the direction and amount of the fault.

B may be carried from *A* vertically up or down on *G–H*, or horizontally on *C–D* or in any radial direction, and usually is taken in some more or less oblique course *A–B*.

Fig. 265. — Fault in shale; the drag and curvature of the beds show that the left side has gone down, the right up. Little River Gap., Tenn. A. Keith, U. S. Geol. Surv.

Normal and Reverse Faults. — If we consider faulting as having taken place merely in a vertical plane then two important cases may

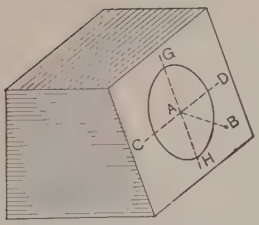


Fig. 266. — Diagram to show possible motion in faulting.

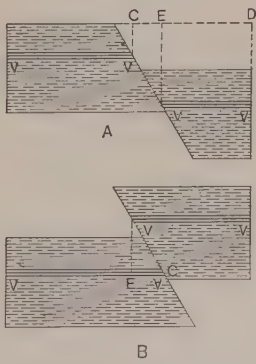


Fig. 267. — Normal and reverse faults.

arise. In *A*, Fig. 267, the hanging wall has apparently slipped down with reference to the foot-wall; a fault of this kind is known as a *normal* fault. In the other case, *B* in the figure, the hanging wall

has apparently been crowded up over the foot-wall and a fault of this kind is called a *reverse* fault. It will be noticed that with the normal fault a particular layer *V–V* has been lengthened apparently by an amount corresponding to the gap *C–E*, while in the reverse fault it has been shortened by an equivalent overlap. With reference to what has been supposed to be their origin, normal faults are sometimes called *tension* faults and reverse ones compression *faults*.

It will be observed that in the above statement normal and reverse faults are said to be *apparently* formed by vertical up or down movements. There can be no doubt but that in many cases the direction of movement is approximately vertical, that is along *G–H*, Fig. 266, or nearly so, but in very many other cases it is not; the motion is oblique along some line *A–B*, and we may even have normal and reverse faults formed by a simple horizontal shove along *C–D*, Fig. 266.

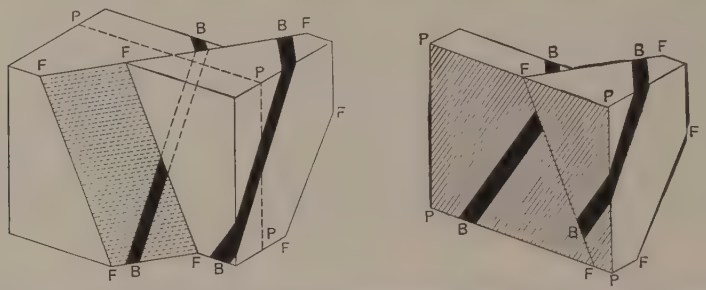


Fig. 268. — To illustrate how normal faulting, as seen in a vertical plane *PP*, may be caused by simple horizontal shoving on the fault-surface *FF*. The particular stratum *B* in *PP* (right-hand figure) appears to have slipped down; modified from Ransome.

This may be seen by careful observation of Fig. 268. The movement of the front block to the right has produced an apparent normal fault; had the movement been to the left we should have had an apparent reverse fault. The terms normal and reverse should, therefore, not be used in the sense of conveying ideas of particular kinds of motion, but merely to indicate the results achieved, as shown in a vertical cross section of the faulted parts.

Components of Faulting. — In order that we may be able to understand and define the geologic structure, where faulting has occurred, it is necessary that we should know the amount and direction of what we may term the components of a fault. This may be understood by aid of the adjoining diagram, Fig. 269. In this *F–A–G–E* represents the horizontal plane, *F–A* is the strike of the fault, that is its intersection with the horizontal plane, and *F–A–D–B* is the fault-surface. Let us suppose that the motion has been such that a particle *A* has been carried to the position *B*, then the line *A–B* joining these two positions is the total displacement, or *slip;* and no matter what path the particle may have followed *A–B* is the

resultant, and its length the measure of the slip. The line *A–B*, however, in order that it may be fixed and determined, must be referred to known constants and this is done by referring it to three planes at right angles to each other. The first is the plane of the

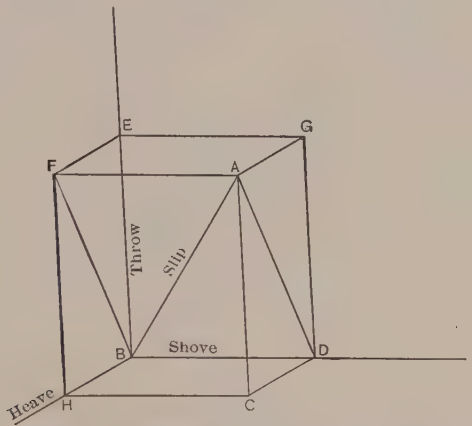


Fig. 269. — Diagram to illustrate and define the components of faulting.

horizon *F–A–G–E*, or its parallel *H–C–D–B*, the second is a vertical plane *F–A–C–H* passing through the strike, or its parallel *E–G–D–B*, and the third is the vertical plane *F–E–B–H*, at right angles to the last one. Now the line *F–E* gives the amount of motion along the horizontal plane at right angles to the strike and this is known as the *heave* of the fault, the line *A–C*, or its equal *E–B*, is the amount of vertical motion and is called the *throw* of the fault, while *F–A*, or *E–G*, the amount of motion along the strike in the horizontal plane may be termed the *shove*, or *strike-slip* of the fault. The intersections of the three planes give the three right-angled axes *H–B*, *E–B*, and *D–B*, meeting in the common point *B*, and these may be termed the *component axes* of faulting. The directions and intercepts on these axes being known, the displacement can be calculated, and the problem of the fault solved.

The heave and throw of faults are the components most commonly recognized, as we shall presently see in considering them in stratified rocks. The reason is that the dislocation is most easily seen in a vertical section *A–G–D–C*, and in this the particle *A* has apparently moved from *A* to *D*, while the amount of shove *B–D*, or *A–F*, may not be at all evident on the surface. The shove is, indeed, as a rule, difficult to estimate in most faults and often it cannot be determined at all.

It is clear that a fault might take place without shove, the movement being wholly in the vertical plane *A–G–D–C*; it might also take place with a vertical fault-surface *E–G–D–B* and in this case there would be no heave; there might be shove, but this might also be wanting and this would be a pure *throw* fault. We

might also have a simple shove, without throw or heave. The last case in which the fault plane is horizontal and there is pure heave without throw or shove, while theoretically possible, hardly seems practicable, the nearest approach to it are certain faults described later under thrusts.

Faults in Stratified Rocks. — While faults occur in all kinds and combinations of rocks they are best, and therefore, most frequently, observed, in stratified beds, on account of the strongly-marked structure which they may displace. With relation to this structure faults may be *strike-faults*, when the strike of the fault and that of the strata are parallel, or nearly so, as illustrated in Fig. 270; or they

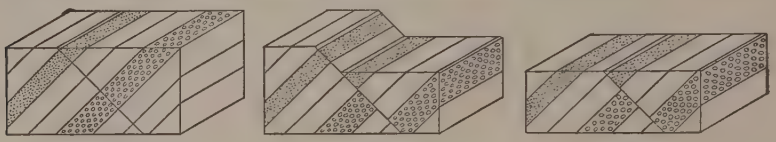


Fig. 270. — Model illustrating strike-faulting in stratified rocks. *A*, before faulting; *B*, after faulting, fault-scarp still uneroded; *C*, surface levelled by erosion.

may be *dip-faults*, when at right angles to the strike of the strata, or nearly so, as shown in Fig. 271; or they may be *oblique faults* when at 45° to the strike of the beds, or approximately so.

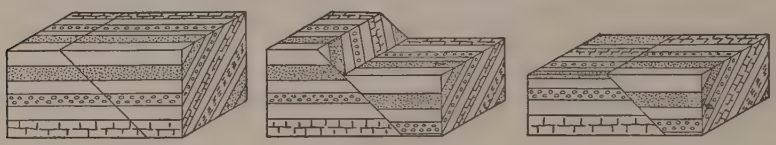


Fig. 271. — Model illustrating dip-faulting; *A*, before faulting; *B*, after faulting, fault-scarp uneroded; *C* surface levelled by erosion, showing offsets of strata.

In the cases shown in the figures the faults are normal ones, they may also, of course, be reversed faults. They are also depicted without real shove, yet it will be noted in Fig. 271 *C* that, apparently, shove has occurred, causing the beds to offset. This sudden offsetting of strata, traced along their strike, is one of the surest indications of a dip-fault. Strike faults are more difficult to perceive and may be easily overlooked; they may cause deception as to the thickness of strata by producing apparent repetitions. See Fig. 270 *C*. Thus, in traversing strata a repetition of a certain set should lead to suspicion of strike-faulting. On the other hand, strike-faults may conceal strata after erosion has occurred. Thus in Fig. 272, where

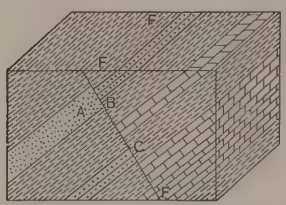


Fig. 272.—Diagram illustrating concealment of strata by strike-faulting.

a reverse fault *FF* has occurred with movement from *C* to *B* and subsequent erosion, there is no outcrop of the stratum *A* at the surface.

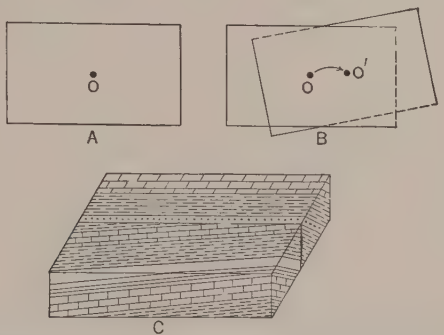


Fig. 273. — Diagram to illustrate rotary motion in pivotal faults. *A*, before faulting; *B*, after faulting; *C*, effect on outcrop after erosion.

Rotary Faults. — The movement of one side of a fault-face on the other side may be attended by rotary motion, as illustrated in Fig. 273 showing the original and final positions of the fault-faces as projected on a vertical plane. Faults of this nature are known as *rotary* faults. They are sometimes indicated, when strike-faults by the strike of the strata on opposite sides of the fault line not being parallel, and in dip-faults by a sudden change in the direction of the strike of strata as the fault line is crossed.

The Magnitude of Faulting. — The scale on which faulting has taken place varies within the widest bounds. It may be but a fraction of an inch as illustrated in Fig. 204, it may be a number of feet and from this up to many thousands. Normal faults attain these magnitudes in the Appalachians, while in the Plateau region faults of several thousands of feet throw are not uncommon, the fractures extending for hundreds of miles and the fault-scarps, being yet uneroded, form lines of cliffs which give character to the topog-

Fig. 274. — Illustrating the forming of a trough by normal faults.

raphy. The Great Basin region presents on a colossal scale the phenomenon of faulting, the area between the Sierra Nevada on the west and the Wasatch on the east being divided into huge blocks by fractures running for many miles, and the sinking of these blocks has produced faults of great dimensions. This will be further alluded to under mountains. Sunken tracts of country by normal down-faulting, as illustrated in Fig. 274, form what are called *troughs* (German *graben*, French *fosse*) and are illustrated in

the valley of the Rhine, the great Rift Valley of Africa with its lakes, and many other places. Such troughs, *graben*, are the direct opposite to *horsts*, which are mentioned on page 228. The relation between them and igneous outflows and intrusions is mentioned on page 212.

Thrusts and Thrust Faulting. — Reverse faults are most commonly found in those regions where folding of the earth's shell has taken place, and the stronger the folding has been the greater and more evident the reverse faults are. Thus, it is especially in the stratified rocks in mountain regions that these results are seen, as in the southern Appalachians. The careful and detailed study of

Fig. 275. — A thrust-fault on a small scale. Near Houston, Okla. J. A. Taff, U. S. Geol. Surv.

old mountain areas has disclosed the fact that these reverse faults have sometimes occurred on a tremendous scale and with the fault having a comparatively low angle of inclination, even being in some cases nearly horizontal. Reverse faults thus having a gently inclined fault-surface are known as *thrust-faults* or simply *thrusts*, see Fig. 275, and they are of such magnitude and importance that by some geologists they are considered quite aside from faults, and in a class by themselves. The fault-surface in this case is spoken of as a thrust-plane.

Such thrusts have been discovered and studied especially in Scotland, in the northern part of the Scandinavian peninsula, in the southern Appalachians, and in the front range of the Rocky Mountains in Montana and British Columbia. The distances which the lower formations may be pushed and made to over-ride the later ones is sometimes amazingly great, ranging from a number of miles up to 70 or more. In Fig. 276 is seen a section representing a portion of the great thrust

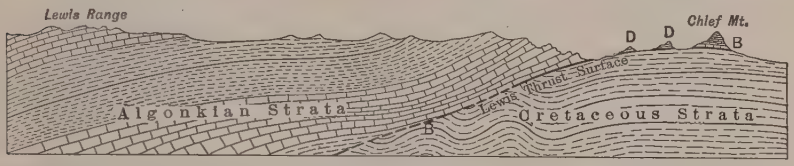


Fig. 276. — Section showing the thrust in northern Montana, whereby very old geologic formations of the Algonkian are made to override the much younger ones of the Cretaceous. *BB* is the surface of thrusting; *DD* and Chief Mountain are erosional remnants of the Algonkian surrounded by the younger Cretaceous. Displacement by thrusting observed, 7 miles; (actual amount unknown). Generalized after Willis.

along the front ranges of the Rocky Mountains in northern Montana. The deciphering of such great displacements is one of the triumphs of modern geological research.

Topographic Results of Faulting. — If a fault of some considerable magnitude were to occur suddenly it would naturally be marked at the surface by a corresponding displacement giving rise, if vertical or nearly so, to a cliff, which is commonly called a *fault-scarp*. Such fault-scarps are not unknown and have been described from a number of places. The connection of quickly formed faults with earthquakes has been previously alluded to (page 230) and an illustration, Fig. 277, shows a fault-scarp which has just been formed with resultant earthquake shock.

Such scarps may be called *initial fault-scarps*. As the process of weathering and erosion works more actively, in general, on the uplifted side, they tend to become dissected, eroded, lowered, and to retreat from the fault-line. Thus they may pass through youthful, mature, and old stages. Finally, the difference in elevation on opposite sides of the fault-line may be worn away completely and thus all topographic expression, initially due to faulting, may be obliterated. This would finish one cycle of erosion on a faulted surface. See Fig. 278.

If now the whole mass should be uplifted with little, or without relative, displacement of the parts and thus a new cycle of erosion inaugurated, similar to that explained under the rejuvenation of rivers and river-work, then the agents of erosion might find on opposite sides of the fault-line rock structures of quite different

Fig. 277. — Waterfall due to sudden forming of a fault-scarp across stream bed; part of movement which caused a great earthquake. Balboa Bay, Alaska. W. W. Atwood, U. S. Geol. Surv.

hardness and ability to withstand their attack. Thus, one side might be lowered so much more rapidly than the other as to leave the latter standing as a cliff or escarpment. This latter would be due, however, not to the initial faulting movement, but to subsequent differential erosion in the following cycle on opposite sides of the fault surface. They deserve, therefore, a different name and have been termed *fault-line scarps* by Professor Davis. They may develop on the side of the block that was originally uplifted and are then termed by him *resequent*, or they may form on the opposite block, and face toward the uplifted side, and are then called *obsequent*. The varying resistance to erosion on the opposite sides of

the fault-line determines naturally which will form, and the course of a very long and old fault-line might be marked in one place by resequent, and in another by obsequent, scarps. Finally, through the completion of another cycle of erosion these also in turn might

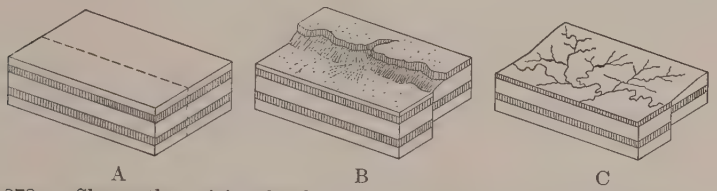


Fig. 278. — Shows the origin, development, and history of an initial fault-scarp. *A*, block of strata containing two harder, more resistant intruded sheets of trap, before displacement. *B*, after faulting and some erosion. The fault-scarp has become mature and has retreated from the fault-line. *C*, approaching the end of the first cycle of erosion; the fault-scarp has been obliterated.

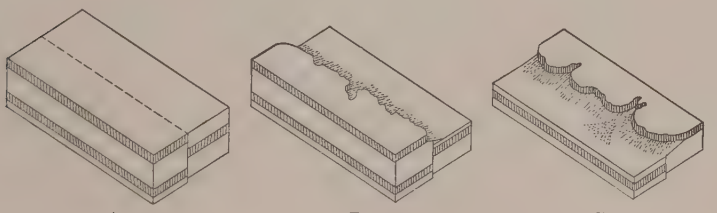


Fig. 279. —Development of fault-line scarps. *A*, faulted block of strata commencing a second cycle of erosion; intruded trap sheets more resistant than the enclosing beds; uplifted block to the right. *B*, after erosion; a fault-line scarp has formed which faces toward the uplifted block and is therefore *obsequent*. *C*, continued erosion has carried away the top trap of *B* and its obsequent cliff and a new one has formed facing the other way, toward the sunken block; this is a *resequent* fault-line scarp; compare *B*, Fig. 278.

be worn away. An understanding of them may be gained by observing Fig. 279, which may be considered a later development of Fig. 278.

The east slope of the Sierra Nevada, the west slope of the Wasatch, and the steep faces of the intervening north and south ranges of the Great Basin, as previously discussed, are held to represent more or less eroded fault-line scarps. At the west base of the Wasatch Range some of the faulting has occurred so recently that fault-scarps may be seen uneroded in the soft fans of alluvial material brought down by the streams. The Plateau region, through which the Colorado river cuts its way, is dominated in its topography by a series of great faults, whose almost uneroded scarps form prominent cliffs. They have been described as fault-scarps, but are very probably fault-line scarps developed in a second cycle of erosion. One of the most striking instances of initial fault-scarps is found in the great Rift Valley of Central Africa whose walls form prominent escarpments for great distances. Examples on a smaller scale are very common. Thus the

sunken tract of sandstones and intercalated trap sheets between New Haven, Connecticut, and Springfield, Massachusetts, is divided into a series of tilted blocks by faulting. It has passed through one cycle of erosion, in which the initial fault-scarps have been eroded away; it is now in a second cycle and the resistant outcrops of trap form prominent ridges, fault-line scarps, both obsequent and resequent, which dominate the topography and reveal the system of faulting which divides the displaced masses. See Fig. 281.

Erosion of Faults. — On the other hand, it is also true that in many places the most profound faults exist, with displacements amounting to thousands of feet, of which there is no trace so far as the surface is concerned, both sides being at the same level. We must conclude in such cases that great erosion has occurred, that the first cycle has been completed, or possibly that the growth of the displacement has been slow enough to be controlled by it. It seems not unreasonable to believe that the latter has often occurred, for we can scarcely imagine that the formation of great faults with thousands of feet of displacement has been a sudden process, but rather the gradual yielding of the shell of the earth in response to the forces brought to bear upon it during long periods of time. The detection of eroded faults, which may be a matter of the highest importance in understanding the structure of a region, is often one of great difficulty, demanding the greatest skill and geologic knowledge.

The detection of faults which do not show any distinct topographic relief is accomplished in a variety of ways. The most common and obvious is the disturbance or discontinuity produced in the structure of stratified rocks, as previously explained. This applies to metamorphic rocks also, but to a lesser extent, because their structures are more complicated and confused, less clear and evident. In homogeneous masses of igneous rock it may not be possible to detect faults, yet even here discontinuity in certain features which they may possess, such as dikes and veins, may lead to the discovery of faults in them.

Origin of Faults. — The immediate cause of faults is comparatively simple and generally agreed upon; they are due either to compression, or to stretching, of the outer shell of the earth. In the first case, through the stress which accumulates from the increasing force of the thrust, the rock masses are strained to a point where they can no longer resist but must give way. Relief occurs through readjustment by movement, either along the surfaces of some previous fissure, or by the formation of a new one. Some effects produced by such movements have been considered under earthquakes. It is also clear that faults of this nature will occur chiefly in places where folding of the strata is a prominent feature and thus, as we shall see later, in mountain regions. If the proc-

ess takes place on a great scale, we may have overthrusts developed.

On the other hand, where segments of the outer shell are (relatively) uplifted, as in the formation of horsts (see page 228), the strata may be under tension and the stretching find relief by fissuring and faulting, the latter produced by the gravitative settling and re-adjustment of the fault-blocks. Thus over wide regions where the strata are not otherwise disturbed, as in the Colorado Plateau, they may be penetrated by fissures and show great displacements along them. And also in the upper portion of up-arching folds there may be tension and cracking, with subsequent gravitative settlement and faulting.

It is natural to think that in regions of folded rocks reverse faults would be the chief or only kind developed, but while it is true that they are essentially confined to such places, the converse of this, that normal faults are found only in unfolded strata, is by no means the case. On the contrary, they are also abundant in folded and dislocated areas as well as in those where the strata are still horizontal, or nearly so. The great majority of faults, in fact, appear to be normal ones due to gravitative settling, for the most part, and resulting in elongation of the crust, and to thus deserve the name; but it should not be forgotten, as shown on a previous page, that normal and reverse are only terms for certain results and that, for example, an apparently normal fault may be produced by compression. In further explanation of what has been said above, if a segment of the earth's shell subsides, it is evident that the beds near the edges of the block will be subjected to tension and eventually to rupture and gravitative faulting. The same is as true, as stated above, if a segment rises, the relative displacement and stretching being the important feature. Thus, in the sinking areas along coast-lines which are receiving heavy deposits of sediment such tensional effects must occur. Also the sinking or rising of such areas may be, and probably is, not uniform over their extent and thus torsional stresses due to the warping will be set up, with fissuring and readjustment of the blocks and consequent faulting. We can hardly imagine movements of the earth's outer shell to take place without either compression, tension, or torsion occurring and producing more or less faulting. As a consequence, all parts of it that are open to our inspection display this phenomenon to some extent.

The *ultimate cause* of faulting evidently depends on those processes within the earth which give rise to compression, or tension, and to movement of segments of its outer shell. They are most strikingly displayed in the formation of its chief features of relief, in mountain ranges for example, and faulting may be considered only a minor and attendant result of their operations. We shall wait, therefore, until the grander results of these processes have been discussed before considering them and in venturing from the known into the realm of the unknown.

CHAPTER XV

MOUNTAIN RANGES: THEIR ORIGIN AND HISTORY

Definition of Mountains. — The term mountain is applied to any higher and more conspicuous elevation of a region which thus stands in contrast to the smaller, lower ones called hills. No exact limit can be set as to the height an elevation should rise above the surrounding country in order that the name should apply, for this is largely a matter of comparative relief, and the mountains of one region where the relief is small would be only hills in another where it is great. In general, one may say that elevations from a few hundred feet high, and up to the loftiest summits in the world, are called mountains. At the very outset it should be understood that mountains, like all forms of terrestrial relief, are not permanent structures, but are always wasting under the attack of atmospheric agencies, though not infrequently renewed by repetition of the same processes which originally caused them, as will be shown in later discussions.

The Grouping of Mountains. — When a mountain more or less approaches a conical shape it is called a *peak*, if it has a considerably elongated crest it is known as a *ridge*. Mountains may be irregularly disposed in *groups*, such as the Catskill Mountains in New York, the Judith Mountains in Montana, the Black Hills in South Dakota, or, as is more commonly the case, they may be aligned in *ranges*, such as the Sierra Nevada, the Caucasus, etc. Such ranges may be made up of a single line of elevations, but more often they are compound, consisting of a variety of ridges whose general direction is parallel, and which thus gives a united trend to the whole range. As we shall see later a range is to be regarded as a geologic unit, formed at a definite time by a set of processes operating toward this end.

A series of ranges, independent of one another, but formed approximately at the same time during a given geologic period and having a common general trend, is known as a *mountain system*. So in the Rocky Mountains a series of ranges constitute what Dana has termed the Laramide Mountain system, while in the eastern United States the Applachian Range, running through Pennsylvania south-

ward, the Acadian Range of Nova Scotia and New Brunswick, and the Taconic Range of western Massachusetts together constitute the Appalachian System.

A *mountain chain* is made up of systems and ranges made at *different* geologic periods, but having a common trend throughout a definite portion of the continental areas. Thus the Appalachian chain contains the very ancient Green Mountains of western New England, and the still more recent Appalachian system. It includes the whole mountainous belt of eastern North America from Georgia to Newfoundland.

A combination of mountain chains, such as those of the Andes, constitutes a *cordillera.* Thus the whole vast mountainous region extending from the eastern front of the Rocky Mountains to the Pacific, and from Mexico northward through the United States and Canada into Alaska, with its various chains, systems and ranges, such as the Rocky Mountains, the Sierra Nevada, the Cascade and Coast Ranges, etc., is collectively known as the *North American Cordillera.*

Classification of Mountains by Origin. — There are three different kinds of agencies to which mountains owe their origin and these are igneous agencies, erosion, and movements of the earth's crust. As we shall see later, no sharp line can be drawn between the different mountain forms produced by these three agencies, but for the sake of convenience and illustration we may distinguish the following types.

Mountains Formed by Igneous Agencies. — These may be subdivided into two classes. In the first the elevations have been produced by *extrusion* of material, and these are illustrated by volcanoes. Some of the loftiest peaks in the world, like those of the Andes (up to 23,000 feet) and Kenia (17,400) and Kilimanjaro (19,700) in Africa, are due to this cause. Many oceanic islands are really great volcanic mountains seated on the ocean bottom and rising, as in the case of Hawaii (30,000 feet), to tremendous heights above their base. See page 107.

Mountains produced by *intrusion* of igneous material are the second class and would be illustrated by laccoliths (page 297) and also in part by necks and stocks (pages 299, 300) although in these cases the work of erosion has also, as a rule, played an important rôle in developing the mountain forms by cutting away the softer sedimentary material, and leaving the more resistant igneous masses exposed. The best examples of laccoliths are found in the region of the Rocky Mountains, especially in outlying districts not far from

the ranges of the main chains. Thus the Henry Mountains in Utah, the West Elk Mountains in Colorado, and the Little Belt and Judith Mountains in Montana are mountain groups produced by laccolithic intrusions. In some cases, as in parts of Wyoming, there are domed hills of sedimentary beds, in which no igneous rock is visible. By analogy, we place these in this same class, in the belief that the cover has not yet been eroded. As we shall see later, igneous intrusion has also helped in the development of many of the great ranges made by folding.

Mountains Formed by Erosion. — It may happen in the general erosion of an uplifted area of country that some parts and places during the process of lowering are left projecting, and these may be of size, sufficient in relation to their surroundings, to be designated as mountains. Some of the buttes in the western United States (page 35) are examples of this. The Catskill Mountains in New York state have been generally referred to as a mountain group of this character, etched out by erosion from a plateau of uplifted sedimentary strata. Looking from its brink into the Grand Canyon of the Colorado one sees a great number of pointed remnants of erosion rising from the depths of the chasm. If they were removed from this stupendous gorge and placed on a plain many of them would form large mountains and the aspect which they present, as one looks upward at them from the bottom of the canyon, is that of a high and rugged mountain range. They are entrenched mountains.

Mountains Formed by Movements of the Crust. — The types of mountains which have been considered in the foregoing discussion, while of geologic interest and in some places forming groups or masses of considerable size, are relatively of small importance compared with the ranges produced by movements of the earth's shell. For it is especially by this agency that the great mountain ranges, which in so many places constitute the dominating features of relief of the earth's surface, have been made. According to the nature of the movement and its results, we may divide the ranges into two classes, a less important one in which they have been made chiefly, or entirely, by dislocation, or *faulting*, and a more important one in which they have been produced by wrinkling, or *folding* of the earth's shell. In the former case the ranges are the exposed edges of great tilted blocks of the outer shell, and in allusion to this fact are sometimes called *block mountains* or, with respect to the structure which they generally show more or less perfectly and which is discussed in the following description of them, *monoclinal mountains*. In the second case, the structures made by folding are typically anticlines

and synclines (page 279) and they may be designated as *folded*, or *anticlinal-synclinal*, ranges. It is particularly in this way that the great ranges and the mountain systems which they comprise have been produced, and a full understanding of them, and of the manner in which various processes have worked together to make them, is of so much importance that they are treated in a section following, by themselves.

From what has been stated in the foregoing, it may now be seen that the different types of mountains according to the agencies producing them may be summarized in tabular form as follows:

Agency	Mode of operation	Illustrative examples
Igneous	Built up by *extrusion of* material.	Volcanoes, Lava Domes.
	Upraised by *intrusion* of material.	Laccoliths.
Erosion	Masses etched out and left in relief.	Buttes, Mesas.
Movements of the Crust	Produced by dislocation, or faulting, of blocks.	Block mountains; Monoclinal type.
	Upraised by folding of crust.	Mountain Ranges; Anticlinal-synclinal type.

While clearly defined examples of each of these types are not infrequent, it is true that all gradations exist between them, and that types of compound nature are most frequent, as will appear in the following sections.

Block Mountains. — As stated above these have been formed by the faulting and tilting of great blocks of the earth's crust. Their structure is most clearly seen in regions of stratified rocks whose beds were previously horizontal; the tilted block then presents an

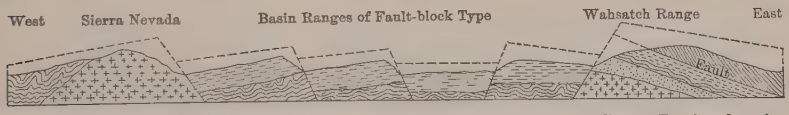


Fig. 280. — Diagrammatic section, East and West through the Great Basin showing how the structure is dominated by faults.

abrupt fault-scarp rising to the crest line on one side and a much gentler slope on the other, the beds all dipping one way in the direction of this gentler slope. It is because of this inclination of the strata in one direction, as contrasted with an anticline in which they dip in opposite directions, that ranges with this structure have been called *monoclinal*. This type of mountains is illustrated by the north and south ranges in parts of the region of the Great Basin

in the western United States, lying between the Wasatch Range on the east and the Sierra Nevada on the west. An east and west section of this is diagrammatically shown in Fig. 280. The production of these mountains by normal faulting has been already alluded to, pages 343 and 347.

The structure here shown is probably most typically developed in the northern part of the Great Basin. Between the great wall of the Sierra to the west, and the Wasatch on the east, the country is filled with many north and south mountain ranges, which are rather narrow and from 10 to 50 miles in length. They may be readily seen in any good atlas on the maps of Nevada, Utah, and adjacent states. Between them lie plains and in places lakes, some fresh but others salt, the region affording the most conspicuous examples of interior drainage in North America, as previously explained under salt lakes. See Fig. 293.

There has been a tendency recently to question the origin by faulting, and the monoclinal nature of the Basin Ranges, and it has been shown that some of them are more complicated in structure than the simple monoclines they were originally thought to represent. The great efficiency of the erosion and transport by wind in the shaping and carving of these ranges in arid regions has been strongly urged by Keyes, who holds it to have been the prominent factor in their production. But while the structure may in many cases be more complicated than was earlier thought, and various agencies may have contributed to their present topography, it still seems true, in the main, that the faulting of the region and the tilting of the

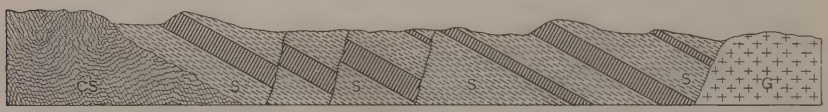


Fig. 281. — Diagrammatic East and West section across Triassic sandstone and included sheets of trap rock. Vertical scale (and thickness of trap) exaggerated. *cs*, crystalline schists; *G*, granite; *s,s*, sandstone and shale; heavily black-lined, trap. Near New Haven, Conn.

blocks produced by it, have been the dominant agents which have given rise to many, if not most, of these ranges.

Block mountains made by faulting and erosion occur also in other parts of the world and many such examples could be quoted. Thus, they are found in south Norway, where in places heavy sheets of igneous rock have preserved the tilted sediments beneath them from erosion and form the crests and backs of one side of the ridges. The same structure is repeated on a small scale in the sunken area of Triassic sandstones running northward from New Haven, Connecticut, to Springfield in Massachusetts. Here also heavy sheets of igneous trap-rock have resisted the erosion and form the crests and backs of the ridges, as may be seen in the accompanying figure, 281.

Folded Mountain Ranges

Introduction. — All the great ranges of the world belong in this class. In North America, the Appalachian Mountains, the great chain of the Rocky Mountains with its subordinate systems, the Sierra Nevada, and the Coast Range bordering the Pacific are examples;

elsewhere the Andes, the Alps, the Urals, the Himalayas and the Caucasus are illustrations. It is especially in them that the greatest exhibitions of geologic phenomena are seen and the lessons, which geology as a science teaches, may be learned. If one desires to know the history of a region, one turns naturally to its mountain ranges, for here may be found the upturned and dissected strata, a study of whose kinds, thickness and fossils throws light upon past events, while their foldings and dislocations show the nature and results of those great dynamic agencies which from time to time have operated upon the outer portion of the earth and given to it the broad distinctive features which characterize it today. They are also the theaters in which many of the forces, which are now modifying the surface of the earth, play their most active rôles, and we can there see the work of erosion, as carried on by water in its varied forms of rain, frost, snow, ice, streams, glaciers, etc., most extensively shown. In most cases, the making of the great ranges has been accompanied, in addition, by igneous activity, and they have been the seat of intrusions and extrusions of molten magmas which have added their quota to the masses of material and to the complexities of structure which the ranges present. It is by reason of these things that they offer problems of the highest interest and importance to geological science and, therefore, merit most serious consideration.

Divisions of Mountain History. — The treatment of the subject most naturally divides itself into three portions, as follows:

a, The *pre-orogenic* period, in which processes and their results are preparing the place and material for the future range; *b*, the *orogenic* period (see page 227) in which the range is made, and *c*, the *post-orogenic* period, during which the range has been subjected to various modifications, chiefly those of erosion, which have brought it to its present condition. It must be clearly understood, however, that no exact boundaries, either of time or of the events occurring, can be drawn for these periods; although they are convenient distinctions for purposes of discussion, they, in truth, merge gradually into one another, so that the whole sequence, like the profile of the range itself, represents a gradual culmination and decline.

Pre-Orogenic Period, Thick Strata. — The detailed examinations which have been made of folded mountain ranges prove that they are composed of masses of very thick sedimentary beds, whose folding and crushing together along a definite axis has produced the elevated tract of country. The length of this axis is that of the range, which may be 50 miles, or 1000 miles, or even more; the

breadth of the tract may be up to 250 miles or more. The maximum thicknesses of the strata, which have been determined in some of the great ranges, are indeed enormous; in the Appalachians nearly 25,000 feet, and as much in the Coast Range, while in others it has been estimated as even greater; 30,000 in some of the ranges of the Rocky Mountain chain, and 50,000 in the case of the Alps. But when traced away from the mountain tract the beds, which the fossils show to be of the same period of deposition, thin out and may even disappear entirely, to be replaced by rocks of a different nature and age. Thus the strata composing the Appalachians have thinned down in the region of the Mississippi to 4,000 feet, (4,000 in Indiana, 5,000 in Iowa) while toward the Atlantic to the eastward of a line from northern New Jersey southwestward to Georgia and beyond, they are entirely wanting. It is probable that in some cases the thickness reported in mountain districts may be due in part to the swelling of the beds caused by the crushing together which they have experienced, and that the first estimates (for the Appalachians 40,000 feet) were thus exaggerated, but the fact stands, nevertheless, that the strata involved are of very great thickness and of the order of magnitude mentioned above. From this and other facts important conclusions regarding the pre-orogenic period may be drawn, as discussed in the following paragraph.

Preparation for the Future Range. — From the general principles which have been previously explained it will be clear to the student that a line of thick heavy sediments can be laid down only in a place of one kind, along the margin of a land that is being actively eroded. If the sediments were entirely of a marine origin, if they consisted solely of lime deposits, of chalk and limestone, this would not be true, for they might then, under favorable conditions, have accumulated in the open sea. But consisting as they do in the great ranges of mingled beds of conglomerates and sandstones, with shales and limestones, it is evident that the seat of deposition must be near the coast-line, either of the land on which continental deposits may form, or of the sea-bottom which receives sediments. Since, however, the whole accumulated mass of strata may be 20,000 feet in thickness, or even more, this must mean that subsidence of the marginal region of deposits took place as the sediments accumulated, for depths of this nature are not found already existing next to the land. The preliminary structure, then, which determines the place of the future range is a subsiding trough into which sediments are deposited from a neighboring land, or lands, undergoing erosion, until a great thickness has accumulated. This relation be-

tween subsidence and deposit of sediments has been previously discussed, page 225, and it has also been stated that an elongated subsiding tract of this nature is known as a *geosyncline*, page 287.

In the Appalachians the strata show by their fossils, markings and structures, such as have been described under sedimentary rocks, and by occasional beds of coal, as well as by the coarseness and characters of the sediments in repeated beds,

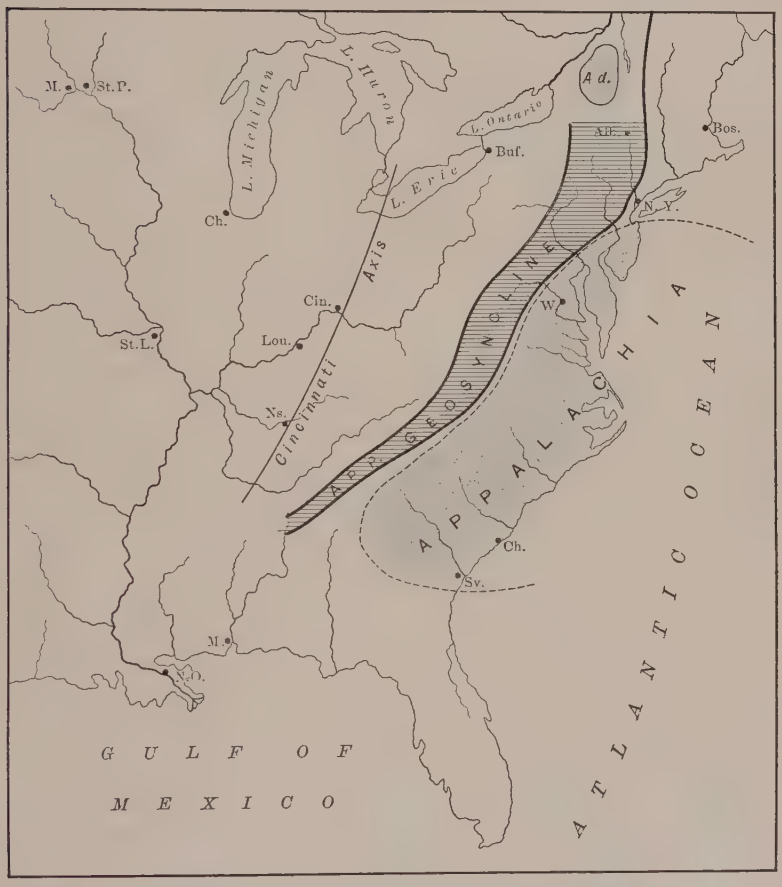


Fig. 282. – Map showing the situation of the Appalachian geosyncline and of the old land of Appalachia. *Ad*, mass of the Adirondacks.

that the deposition took place in shallow water, and was partly marine and partly continental in nature, and also that the process of subsidence was not a steady gradual one, but interrupted, with periods of upbuilding to land surface and of low uplifts, producing various configurations of land, swamp, and shallow sea. The history of these changes is fully discussed in the second part of this work. That the sediments are continued westward toward the Mississippi and beyond,

growing finer, sandstones giving place more and more to shales, and limestones becoming more abundant, proves that the seas and water bodies lay in this direction, since the land deposits tend to give way to those more characteristic of marine origin. It follows as a necessary deduction, that, as stated above, there must have been a land whose erosion was furnishing the sediments and this land, to which the name Appalachia has been given, lay to the eastward of the subsiding trough. There were also other land areas to the northward and westward of the great embayment. Since Appalachia was a land, and being eroded, it could not receive sedimentary deposits, except local ones of a continental nature, and accordingly, we find no marine deposits of this geological age between the eastern edge of the Appalachians and the Atlantic. In the adjoining plan, Fig. 282, the generalized outline of the geosyncline is given which received the heavy deposits forming later the Appalachians from southern New York to Georgia. The process here outlined continued until the closing of the coal-making period of western Pennsylvania and the 25,000 feet of sediments had been deposited, when the orogenic one commenced.

Similar processes have preceded the making of others of the great ranges. The Sierra presents the marginal deposits of a land that lay to the eastward where the Great Basin is now situated. After the mountains were formed their erosion produced the material now seen in the Coast Range, so that here the mountain-making was successively transferred westward toward the Pacific. In the Alps the lands lay to the northward and their sediments were deposited in the sea to the southwestward, while in the Caucasus the old lands were to the southward and the sediments were laid down in seas stretching northward over Russia. It may be thus accepted as a general principle that on one side or the other of the great ranges lies an area of much older rocks representing the source of the material which composes them, and upon which, therefore, marine deposits of that period are wanting. It may be that the old lands have been afterwards depressed and covered by still later deposits which mask them, but they must still be there.

Orogenic Period and the Forces Involved

The period of relatively quiet preparation which has been discussed, of long-continued erosion and sedimentation and slow changes of level of land surface and sea-bottom, gives way to a more active one in which the earth's outer shell yields to pressure which displays itself by enormous thrusting in a lateral direction, tangential to the earth surface. By this thrusting the accumulated load of sediments is thrown into folds, crushed and mashed together, so that the thickened mass rises and the mountain range is made. This constitutes the orogenic period. The process and its results thus simply stated are in reality very complicated, with different phases and with divergent features in different regions, some of the more important of which demand separate consideration. We shall take up first the operating forces and then the results produced.

Evidences of Lateral Pressure. — That the ranges have been made by the crushing together of the geosyncline with its burden of sediments by forces acting in a lateral or tangential direction is

clearly evident by the structures which they present. Thus, in the zone of most intensive folding, the folds not only become closed so that their limbs are in contact (see page 286), but they are even more severely compressed, with under folding as a result, and the production of fan-like structure, as it is termed. This is shown in the adjoining section through a portion of the Alps, Fig. 283. It

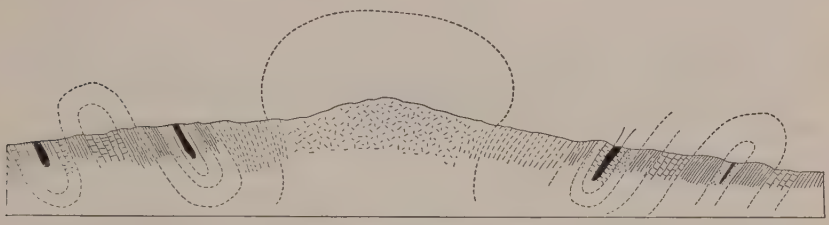


Fig. 283. — Generalized section across a zone of intensive folding in the Alps. In the center is an intrusion of granite flanked on either side by gneisses, schists and other metamorphic rocks. The metamorphism and folding are less pronounced as one recedes from the central zone. The folds have been largely cut away by erosion and the structure revealed.

would be impossible to imagine the formation of such structures except by traverse compression with relief by upward movement.

Experimental Proof. — Again the varied phenomena of folding shown in the mountains may be imitated by lateral compression of a sequence of artificial strata composed of layers of some plastic substance such as wax or clay placed upon one another. If these are laid in a firm trough or box, one end of which may be forced inward by the turning of a screw, structures are produced whose character is shown in Fig. 284. The displacements and dislocation; the folding and faulting of the strata produced in miniature by this method are precisely similar to those observed on a great scale in the mountain ranges.

Cleavage. — In the discussion of metamorphic rocks (page 320) it was shown that this feature of rocks, especially of slates, was due to great pressure, and that the planes of cleavage were perpendicular to the direction of pressure. Now the rocks of the great ranges in the zone of intensive folding are not only apt to be metamorphic, but also to show cleavage, being turned into schists and slates according to their particular composition. This becomes more evident as the inner portions of the compressed masses are exposed by erosion. Observation shows that the planes of cleavage usually stand at high angles and are not infrequently perpendicular, while the strike of the cleavage planes is, in general, more or less parallel to the axis of the range. The direction of the compressive force,

thus indicated by the cleavage, is the same as that shown by the folding.

Faulting. — It is obvious that such extreme folding as occurs could not take place without frequent rupturing, breaking and displacement of the strata, and consequent faulting. We find, therefore, that the phenomenon of faulting is very common in mountain

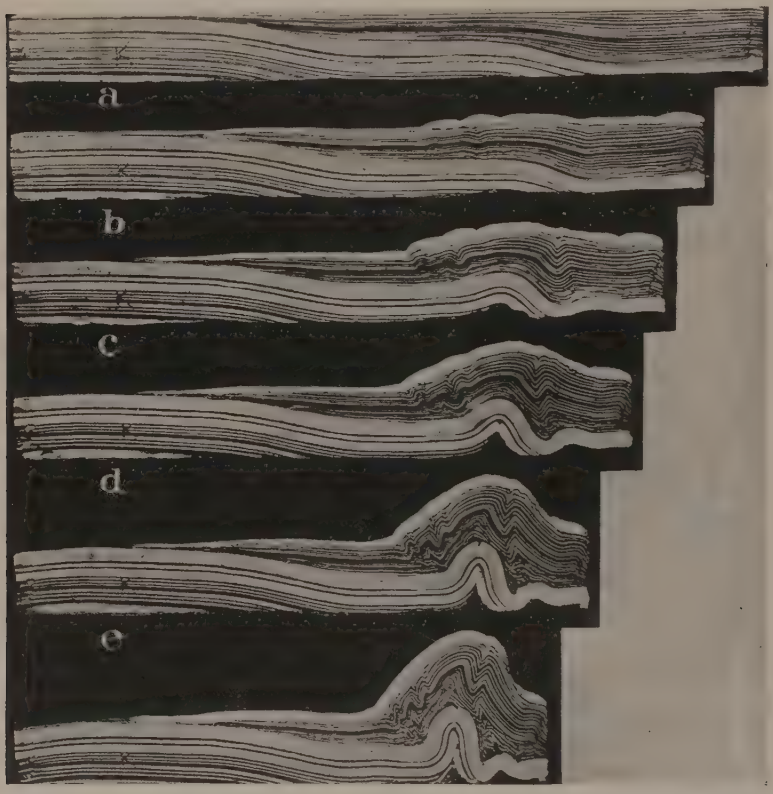


Fig. 284. —Layers of Wax and Plaster folded by lateral pressure, imitating structures found in folded mountain ranges. The thrust is from the right and in successive layers, from *a* to *e* the amount of shortening can be seen. (Willis, U. S. Geol. Surv.)

ranges; both normal and reverse faulting being found. But especially notable, as indicative of the nature and direction of the orogenic forces, are the great thrust-faults which are found in many ranges. They have been described under thrust-faulting and have been found affecting the mountain structure of the Appalachians, the Rocky Mountains, the mountainous regions of Scotland, Norway and in the Alps. The low angles of the surfaces of the major faults

and their trends parallel to the axes of the ranges are indicative of the lateral compression, or approximately horizontal thrusting, which has produced them.

In summation then, we may accept it as a well-grounded fact that the folded ranges have been made by the lateral shoving, or squeezing together, of the stratified beds laid down in geosynclines. See Fig. 285.

Amount of Compression. — No better idea of the magnitude of the forces involved and of the masses operated upon can be had than in considering the amount of compression which investigation shows has actually occurred in the making of some of the great ranges. In the Appalachians estimates of 40 to 50 miles, and in some places even more, are given for the distances the original width of the strata in the geosyncline has been shortened by the mashing together of the mass. If some of the more extreme estimates are correct the folded strata in Pennsylvania, if smoothed out like a crumpled blanket, would also cover a considerable portion of Ohio. In the eastern Rocky Mountains in British Columbia, McConnell estimates an original width of 50 miles has been shortened by compression into one of 25. For the Coast Range in California the shortening is about 10 miles according to LeConte's data. In the classic example of the Alps, whose folding has been measured by Heim, the total shortening is equal to 74 miles. Thus in the production of the great ranges the breadth of the geosynclines has been diminished from 10 to 50 miles, or even more, and in the zones of intensive folding and mashing the reduction has been one half or more. If the original strata were 20,000 feet thick at these points the compressed material would be double this in thickness, and were it not for the agency of active erosion in cutting the mountains away as they form, the heights of the ranges would be far beyond anything now known.

Influence of the Positive Elements and Direction of Thrust. — The old upland along whose margin the sediments have been deposited forms a positive element, or horst, in the architecture of the outer shell. It tends to rise as the geosyncline tends to sink, and as it becomes eroded the stronger massive rocks, igneous and metamorphic, of which its lower levels are composed, tend to rise toward the surface. It thus becomes steadily more massive and resistant, a more unyielding block or element in the shell. The sinking zone of accumulating sediment is one of weakness; whether the sinking is the cause for the accumulation of the sediments, or the result of it, has been previously discussed. Finally, when the shell yields to

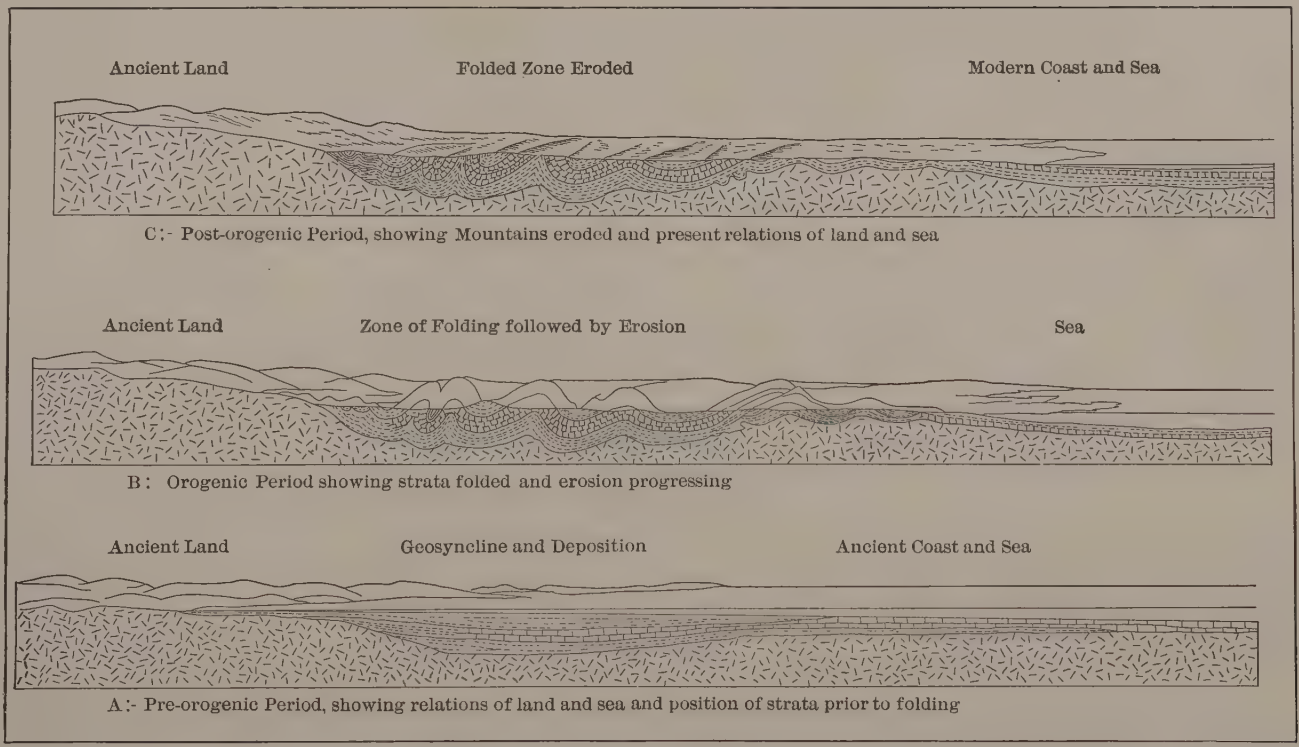

Ancient Land
Folded Zone Eroded
Modern Coast and Sea
C:- Post-orogenic Period, showing Mountains eroded and present relations of land and sea
Ancient Land
Zone of Folding followed by Erosion
Sea
B: Orogenic Period showing strata folded and erosion progressing
Ancient Land
Geosyncline and Deposition
Ancient Coast and Sea
A:- Pre-orogenic Period, showing relations of land and sea and position of strata prior to folding

Fig. 285. — Diagram illustrating the origin and history of a folded range, such as the Appalachians. Modified from Willis, U. S. Geol. Surv.

compression the sediments are driven against this more resistant mass and are crumpled up. The result is that the beds appear to be carried against the previous continental area, or areas, by a thrust coming from the direction of the sea. It seems probable that this is largely apparent, due to the greater resistance of the horst, and that the contraction is general, so that the geosyncline is not only narrowed, but also shortened. Thus the general trend of the mountain chains seems to be determined by the situation of the old lands which form the positive elements at the time of their formation, and the ranges may, therefore, be said to roughly outline ancient sea-coasts.

Thus the Appalachians from southern New York to Alabama indicate the former marginal coast line of the old continent of Appalachia. It is believed that the trend of the Alps has been determined by the old land masses of central France, the Vosges, the Black Forest and Bohemia, and this relation is indicated on the outline map, Fig. 286.

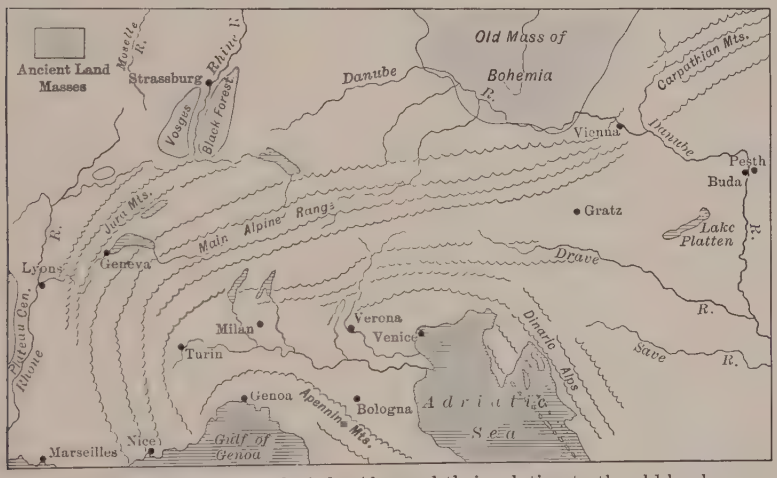


Fig. 286. — Showing the trend of the Alps and their relation to the old land masses.

The same is true of other ranges, like the Coast Range of California, or the range of the Caucasus between the Black and Caspian Seas, where the sediments laid out on the land margin and on the sea-bottom, now represented by the level plains of Russia, were driven against the old land of Armenia, from which they were derived.

Work of Igneous Agencies. — While the making of the folded mountain-ranges by compression of the sediments appears to be independent of direct igneous action, and in some cases there are long distances in the ranges in which no igneous rocks occur, as in the Appalachian Range in Pennsylvania and West Virginia and in

the Coast Range in California and Oregon, it is nevertheless a very common thing to find that, attendant upon the folding, there has been an upwelling of magma from below, which is shown by the intrusions, or extrusions, of molten rock, and often of both, which are so frequently found in many ranges. The effect of this is to greatly add to the height and size of the uplifted mass and to thus increase the volume of the range. Probably the most effective way in which this happens is in the intrusion of great bathyliths, (see page 300), which are usually composed of granite, into the inner, lower portion of the range. A granite intrusion of this nature only becomes exposed later by deep erosion, and is then often spoken of as the 'granite core' of the range. As a result of the intrusion, combined with the folding and mashing of the strata, the latter are subjected to profound metamorphic effects and may be changed

Fig. 287. — Illustrating the granite core of a mountain range as exposed after prolonged erosion. The strata on either side of the bathylith have become crumpled and metamorphic.

over wide areas to gneisses and schists, such as have been described in Chapter XIII. Instances of this are seen in some of the ranges of the Rocky Mountains' chain, in the northern Coast Range, in the Alps, the Caucasus, and others that might be mentioned, Fig. 287. The older a range is the more deeply it will be eroded, and the more likely we are to find its rocks harder, more resistant, and the unaltered stratified kinds to be replaced by metamorphic and igneous ones. The uprising of these great domed surfaces of granitic rock also generally adds to the elevation by carrying up the stratified ones upon them. We shall have occasion to consider this later when the results of erosion are discussed.

Invading granitic masses of this character are a marked feature of many mountainous tracts, such as those of eastern Canada, of New England, (in the Green and White Mountains) in North Carolina and in the Sierra Nevada for example, while the Alps, and the Caucasus, as well as the mountains of Scotland and Norway, can be mentioned as examples for Europe.

Where intrusions of molten magmas have occurred they may not only make great bathyliths, but pressing upward where relief is found in places and belts of weakness caused by folding, fractures, and dislocations, they may form intrusive sheets, laccoliths, chonoliths, plugs and stocks, or bosses. Or, attaining the surface, they may extrude as lava flows, often of great extent and, if the physical conditions are right, give rise to volcanic action with the production of cones of large volume composed of tuffs and breccias. The Rocky Mountains in Colorado,

Wyoming and Montana are a striking example of this, and during the orogenic period were the scene of great volcanic activity which became especially pronounced toward its close, when many groups of active volcanoes existed. This igneous phase lasted long into the post-orogenic period and its dying remnants are still seen in the Yellowstone Park. As a result of the folding and faulting of strata, and the intrusion and extrusion of magmas, there were produced ranges with geologic structures of wonderful complexity, which are now revealed to us by the great dissection due to long erosion. The same features in greater or lesser degree are true of many other mountain ranges, and they are illustrated in Fig. 288.

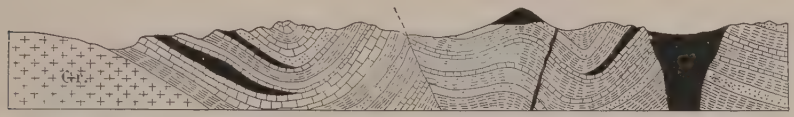


Fig. 288. — Section illustrating intrusions of igneous rock (black) in a folded and dislocated mountain region. *Gr*, edge of a granite bathylith.

Types of Mountain Range Structure. — It is evident from the preceding discussion of folded ranges, dependent upon the folding and fracturing and the intrusion and extrusion of molten material, that varied types of structure may be found in them, some of which may be comparatively simple, while others may be extremely complex in nature. Some of these have been already described and illustrated by sections, but a few other important instances may be mentioned.

Fig. 289. — Section *SE* and *NW* across the Jura Range, showing simple structure and symmetrical folding.

Thus in some cases the structure is very simple and the ranges are composed of stratified beds only, thrown into more or less regular folds. The Jura Mountains of Switzerland, a western member of the Alpine system (see Fig. 286) have long been considered as a classic example of this and a section through this range is given in Fig. 289.

The Appalachians from Pennsylvania southward present an ex-

Fig. 290. — Section 12 miles long illustrating Appalachian structure near Greenville, Tenn.; slightly modified from Keith and Willis.

ample of a much more complexly folded range; in them folds of various types, closed, asymmetrical, and overturned, as well as faults and thrusts, are common. A portion of their structure is illustrated in Fig. 290. This complexity becomes so pronounced in some ranges, as in the Alps, that by the overturning of folds and the successive driving of huge rock sheets over one another by thrust faults, which

extend for tens and possibly even for hundreds of miles, structures of almost bewildering intricacy have been produced.

Origin of the Compressive Forces. — When it was believed that the earth consisted of a relatively thin crust resting on a highly-heated liquid interior it seemed easy to explain the origin of folded mountains by assuming that there was a regular contraction of the earth's mass

Fig. 291. — Folded and upturned strata in a mountain range. South of Heaven's Peak, Livingston Range, Montana. Vertical range 2,000 feet. R. H. Chapman, U. S. Geol. Surv.

from loss of heat, and, since this contraction was greater in the heated interior than in the cold outer crust, the latter was folded up as it gradually sank upon the shrinking core, very much as the skin wrinkles upon a drying and contracting apple. This view, for a variety of reasons which have been stated, we can no longer hold; the earth behaves like a relatively solid, rigid body, it cannot be wholly, or even largely, fluid within, in the ordinary meaning of the word, and, except locally or to a superficial depth, it may not be hot, at least in any such sense that it could experience the notable contraction from loss of heat demanded for the origin of the folded ranges.

The evidence, however, that these ranges have been formed by lateral compression, acting with tangential thrusting movement, is, as has been shown, direct and positive; we cannot conceive of forces acting in any other way which would yield such results. Since the contraction in a horizontal sense is evident, it is for us to find an

explanation of it; is it due to contraction in a vertical sense, that is, radial contraction of the earth as a whole, or may it be explained in some other way? The volume of the earth is so vast, that, in considering this question, we are liable to become confused by the multiplicity of the processes which affect it, but by regarding smaller objects whose dimensions and properties we can hold more easily in mind, the only way in which we can logically conceive of the surface of a spherical mass contracting is by a lessening of the volume of the object as a whole, and by simple analogy we must imagine this to be the case with the earth.

This, of course, is true only so long as we deal with objects of a truly spherical form; if the form be not spherical, and if for any reason there are changes in it, then there will be changes in the surface area, even though the mass-volume remain the same. Based on this fact the view has been advanced that, since the earth is not a true sphere but an oblate spheroid (see page 245), whose oblateness depends on its rate of rotation, and since the latter has supposedly been diminishing during geologic time, the earth has been becoming more spherical and in consequence its surface area has decreased; this, it is stated, would involve contraction of the crust and cause the formation of mountain ranges. But as Chamberlin has pointed out, in the change from more to less oblateness of form, the equatorial bulge lessens, while in the polar regions out-swelling occurs. The contraction is, therefore, felt in equatorial regions with the shortening of the equatorial circumference, and, as a consequence, the mountain ranges should occur in this belt and have a north and south direction. In polar regions the crust would be in a state of tension, or stretching, and compressional mountain-making would not occur. In latitude 33° there would be neither compression nor stretching and in this zone the north and south ranges would die out. A mere glance at the map of the world is sufficient to show that the distribution of mountain ranges in no wise coincides with this hypothesis. They are as common north of 33° as they are south of it, the neutral zone near 33° is marked by some of the greatest ranges of the world, the Caucasus, the Himalayas, and others of Asia whose trend is east and west, while the Antarctic continent has notable ranges. The case would be better for this hypothesis if it could be shown that its axis of revolution had been changing place within the earth, or in other words that the situation of the poles upon its surface had wandered during geologic time, and attempts have been made to show that this has occurred. They do not, however, take into account the mathematical and physical difficulties involved in such an assumption and until these have been considered no importance can be attached to this view.

If, then, we are required to rely on contraction of mass as the ultimate cause for the contraction of surface area, which produces the lateral pressure, it is possible to conceive of this as occurring from different causes either mechanical or chemical. They may be briefly discussed.

Mechanical Causes of Shrinkage. — Probably the view which is most commonly held to account for contraction is the loss of heat.

This is the survival of the idea mentioned above as held when it was believed the earth was liquid within, but changed to accord more nearly with later knowledge. It supposes the earth to be solid and rigid but very hot within (see page 247) and by the progressive loss of this heat the shrinkage to be caused. We cannot say positively that this view is untrue, but if several essential facts be taken into account it seems improbable. These facts are as follows:

If we introduce a quantitative element, as Chamberlin has suggested, it is clear that every mile of shortening of an arc of the world's surface requires a shortening of the diameter of $\frac{1}{3.14\frac{1}{16}}$ mile, since this is the relation of circumference to diameter, or in round numbers a shortening of the radius of one mile shortens the circumference six miles. In the case of the Alps, the shortening of the arc has been computed to be 74 miles, for the Appalachians 46 miles, and other ranges in proportion. To make the ranges now existent it used to be thought that a shortening of the radius from 20–40 miles at least from Cambrian time to the present was necessary to give the requisite contraction and surface reduction, but the more recent work of Heim and other geologists in the Alps and elsewhere shows that these figures must be greatly increased. Heim now thinks that the original Alpine area before folding was from 400–750 miles broad and that this has been reduced to 100 miles in the crushing together. The reduction for the loss of a given amount of heat has been calculated and the results prove that to accomplish the necessary shrinkage a very improbable loss of heat would have had to occur. Moreover, every explanation for the cause of the contraction that is offered must take into account two things: first, that both the paleontologic study of the life history of the earth, and other facts relating to the formation of the stratified rocks, show very clearly that essentially similar conditions of land and water, of atmosphere and climate, have obtained upon it for an immense period of geologic time, during which most of the great ranges we know have been erected, and second, that mountain-making has not been a regularly progressive process, but a periodic one, occurring in cycles, interrupted by long periods of earth-rest, as we shall see more fully discussed in the second part of this work. The simple loss of heat alone does not explain this latter fact, nor can we believe that within the historic period of geology the outer shell of the earth differed essentially in its heat content from that of today.

Of other mechanical causes suggested one is the transfer of molten material from within to the surface, causing the outer shell by its own weight and that of the added material to tend to sink in, and thus to be under compressive strain.

This is a real cause so far as it goes, but it does not go far. The extrusion of 1,000,000 cubic miles of lava would furnish but a small fraction of the shrinkage required for one of the great ranges.

In the theory of isostasy, (see page 250) it is assumed that, as the heavier segments of the earth sink, matter is crowded toward, and against, the rising positive segments, or horsts, and that this flowage produces superficially a wrinkling of the outer crust which gives rise to mountain ranges. While this might explain the grouping of the ranges in festoons about the positive elements, or old continental shields discussed later, it does not explain the ultimate cause of the rising and sinking of the segments themselves. Other causes have been suggested, such as the transfer of heat from an inner core to an outer zone, but not necessarily to the actual surface whose temperature remains substantially constant. It has been considered that no unreasonable fall of temperature of the inner core would produce in the outer shell, which receives heat faster than it loses it from the surface, an expansion yielding the results demanded; this could not be, of course, a process continuing indefinitely, but, according to the view, is still in operation. Still another view suggests the condensation of matter toward the center, with a growing density of the mass, and a consequent lessening of its volume. Such views are, however, purely hypothetical and their correctness we are able neither to affirm nor deny. The last one, however, bears so closely on the chemical explanation given below that it seems a necessary consequence of it.

Chemical Cause of Shrinkage. — We have had occasion in several places to refer to the part which the recently discovered fact of the chemical disintegration of matter may play in geologic processes. Some of the elements are known to decompose into others, in part gaseous ones. Thus uranium is held to decompose into products of which lead is one and helium, a gas, is another. The list of such radio-active, or disintegrating elements, with advance of knowledge, appears to be increasing. With the escape of the volatile substances, some of which, like helium, would probably not be held by the earth but would pass off into space, there could be a condensation of volume. It may be that this property of matter is much more general than has been supposed, and occurs on a scale which would make it applicable to the present problem. But the process of disintegration is attended by the production of a relatively enormous amount of heat, and if we imagine it as occurring on such a scale that it becomes the factor in the making of mountain ranges by contraction, we must also deal with the heat generated. We should be forced to consider the earth as growing hotter instead of cooler, and from many considerations this would be objectionable. This view, however, has not yet advanced beyond the speculative stage and can be only tentatively regarded.

General Summary. — From the discussion given above as to the ultimate origin of orogenic forces, it is clear that at the present time we are not able to draw a definite conclusion, or one that would meet with general acceptance. It seems reasonably safe to say that they have been caused by contraction of the mass-volume of the earth, and that it is probable that this contraction is not a simple process but due to a variety of causes whose complexity we are only beginning to appreciate. This is the more evident when we see that the orogenic process has not been a regularly progressive one but

periodic and, perhaps, rhythmic, in its operation. If the outer shell were sufficiently rigid to withstand the contractive strain, we might understand this periodicity as the times of yielding to accumulated stress, but since we see this layer constantly yielding to it with the production of faults, earthquakes, subsidences, etc., it is clear that it cannot be always yielding to stress and accumulating it at one and the same time. The cause of this periodicity is at present a mystery, which it may be hoped further scientific knowledge may unveil.

Origin of Block Mountains. — The folded ranges, as we have seen, are due to the crushing of thick deposits laid down in those broad, concave sinking tracts on the ocean borders which have been termed geosynclines. The resultant crushed mass has been appropriately called a *synclinorium* by Dana, that is mountains formed in a syncline. In a similar way we can imagine the earth's crust warped into broad upward folds, or domes, of relatively low uplift to which the name of *geanticlines* has been given. If a dome of this character is relatively small it may be able to sustain itself, but if of very wide extent, several hundred miles broad, and thus corresponding to the great geosynclines in size, it may be unable to do so, the arch may break down with the production of normal faults and tilted blocks. Whether we regard such a movement as produced by contraction of the crust with inflowage of matter beneath it and consequent uprise, or as a rising of a positive element or horst (see page 227) according to the theory of isostasy, is largely a matter of definition, the result is the same. If the dome remains unbroken it forms a plateau which erosion may carve into mountains; if faulted and broken, the results may be those seen in the Great Basin and previously described.

The Black Hills of South Dakota, and on a smaller scale the Little Rocky Mountains of Montana, represent domed uplifts which have been competent to sustain themselves. The strata on such an uplift need not be necessarily thick,

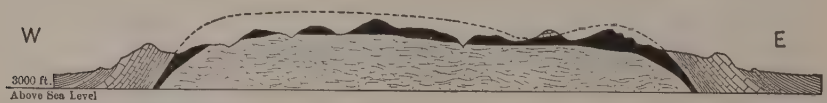


Fig. 292. — Section through the Little Rocky Mountains, Montana. Main dome of gneisses and schists. Black shows remnants of an intrusion of porphyry. At borders, upturned strata, remains of which still rest on the porphyry. Length of section about 10 miles.

such as would accumulate in a sinking geosyncline, and in their cases have been largely removed by subsequent erosion, and are found as upturned ridges about the flanks of the dome, see Fig. 292. The rising of the arch tends to lower the local pressure and to be accompanied by inflow and, at all events, by upflow of material which is marked by the intrusion of igneous magmas as stocks, dikes and sheets, and in areas of weakness and relief of pressure on the borders as lacco-

liths; these intrusions help to swell the volume of the uplift. Subsequent erosion carves the mass, whose general ground-plan is more or less elliptical or even circular, into a group of mountains and valleys.

In the case of the Great Basin, the arch has broken down, leaving the Sierra on one side and the Wasatch on the other as the former piers; it seems to have been too vast to have been able to sustain itself, see Fig. 280, and the sunken blocks form ranges, as previously described, Fig. 293. Here, too, the same up-

Fig. 293. —Eroded face of a block mountain range near Lake Abert, Oregon. W. C. Mendenhall, U. S. Geol. Surv.

welling of magmas with intrusions and vast outflows of lava have occurred. This region has been considered by some to have been subjected to great tension, or stretching, of the crust, with breaking down into block mountains by subsidence, but it is difficult to account for such an effect and it seems more reasonable to regard it, and similar tracts, as broken down geanticlines, thus bringing them into correlation with the general contractive movement of the earth, and with folded ranges.

Geological Date of Mountain-making. — The geological period at which a geosyncline has been crushed, and the strata compressed into a mountain range, is determined by observation of the age of

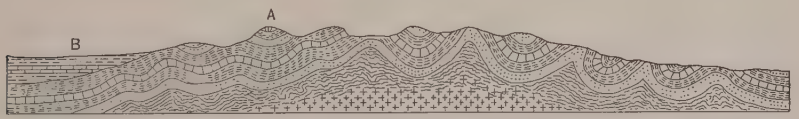


Fig. 294. — Illustrating determination of the date at which mountain-making occurs. *A* are the youngest strata involved in the folding; the folding is younger than these; *B* are not concerned in the process and are later; the folding is older than they are.

the latest strata involved in the folding, and of the oldest beds resting undisturbed by mountain-making processes upon the disturbed rocks about the mountain flanks. The date of folding is obviously younger than the folded beds and older than the undisturbed ones. This will be clear from an inspection of Fig. 294.

Thus by this process, it has been determined that the Appalachians

were formed for the most part during the Permian period, the Rocky Mountains at the close of the Cretaceous and, therefore, later; the Alps mainly at the close of the Miocene period and thus still later. The accuracy of the method evidently depends upon the shortness of the interval between the times of deposition of the two sets of strata *A* and *B* in the diagram. Of the actual length of time consumed by the deformative process before folding and uplift ceases, we know nothing; from the human point of view it must be very great; from the geologic standpoint, we know it must be short compared with the immensely long period of relative quiet and preparation preceding it.

The Appalachians were long in making, the process lasting through several geologic periods. The first thrust came in the Lower Cambrian, the second in the Taconian, then in the late Devonian came another; still another in the earliest Pennsylvanian and finally, the culmination in the great thrust in Permian time.

Post-Orogenic Processes

While we may classify mountains by the structural processes which have aided in their formation, it is not to these processes alone that the mountains as we now see them are due. For the uplift of a dome, for example, like that of the Black Hills, would of itself furnish us only with a plateau, not necessarily with mountains. Hand in hand with the raising of the masses goes the work of erosion, that mighty chisel of Nature, which shapes and carves them into the mountain forms familiar to us. And as by simple differential erosion we see projecting buttes and rock spires left as remnants, so it is conceivable to us that this process alone, aided by underlying structure, might, from a relatively level country, etch out forms whose magnitude would compel us to call them mountains. The residual mountain blocks situated in the trough of the Grand Canyon are an example of this, as previously stated.

The work of erosion, then, is of the greatest importance in a full consideration of mountains, it begins with the first rising of the masses, proceeds while the orogenic forces are at work, and continues long after they have come to rest. As its results become especially marked in this last stage, it must be considered the chief agent in mountain-making in the post-orogenic period, and some of its more important results may now be considered.

Characters of Young Mountains. — So long as the compressive orogenic forces are at work a mountain range will be growing, in so far as its structure is concerned. Whether it will be actually rising in height, or not, depends on the adjustment of the varied forces at

work upon it, the lateral pressure, for example, in a folded range which tends to make it rise and the work of erosion which tries to cut it down. Always, during this formative period, there is this struggle going on, and the range as it exists at any time is the resultant between the two. When the orogenic movements cease then denudation has full sway and, ultimately, with the lapse of sufficient time and provided no renewal takes place, the range must be cut down, base-levelled and extinguished by the ever-gnawing erosion. In this process various stages are to be distinguished. When the range is at its maximum of elevation then the erosive agencies are most severe; to the work of running water on steep slopes is added very commonly the effect of frost, snow and ice. It may happen also at this time that the rock material exposed to erosion consists of the later beds laid down in the geosyncline, which have suffered less metamorphism than the deeper, older ones, and are thus softer, or less resistant, to erosive attack. If igneous injections and extrusions have contributed to swell the volume of the range, it will also be the

Fig. 295. — Outline view of a distant youthful mountain range of the Sierra type.

more easily eroded tuffs and lavas that are first exposed. Hence, in general, the outer material is more easily cut away, and with progressive erosion the inner core becomes more and more resistant. Thus, in the early history of a range not only is the severity of attack of the eroding forces increased by the greater height, but they are more apt to find less resistant material to work upon. In consequence, the masses become profoundly graved and rugged, characterized by peaks and towering rock pinnacles, which alternate with deeply scored valleys. The strongly notched outline of such a range at a distance presents a saw-toothed appearance, which has led to the Spanish name of Sierra, a saw, being given to them. See Fig. 295. The topographic forms of the peaks and ridges and of the intervening valleys in such a youthful range obviously depends on the nature and structure of the rock masses presented to erosion. A discussion of them would carry us too far, but some important features are described later.

The Jura Mountains of Switzerland, see Fig. 289, present a type of very youthful dissection; here the structure forms produced by folding still give the dominant topographic features, which erosion has, as yet, been unable to essentially modify. Ranges like the Alps, the Himalayas, the Caucasus and many of our

Rocky Mountains' system, are still in a youthful stage of dissection, although their topographic relief, that is their mountain forms and valleys, is dominantly one of erosion, and not evidently of folding, as in the Jura. The term youthful in this connection must be understood to be a merely relative term and not one of absolute time; actually one range may be much older than another and yet, on account of its greater mass, difference in material, or situation as to climatic severity of erosion, be in a more youthful stage of dissection.

This has been previously explained with respect to river valleys, page 47, and is equally true here. It is only in a very general way that we can say that the higher mountains are the younger ones.

Characters of Old Mountains. — If erosive processes continue their work of degrading a mountain mass, unhampered by further upward growth from orogenic agencies, the range gradually passes into a *mature* stage. The sharp peaks and roughnesses tend to disappear, the valleys to widen and open. And as the work continues it goes more slowly as the inclination of slopes lessen, and as, in most cases, the more resistant metamorphic and crystalline igneous rocks of the inner core, or axis, are reached. Thus in an old range, maturely dissected, we are apt to see gently modeled, rather smoothly-rounded forms and outlines, as suggested in Fig. 296, which may be compared

Fig. 296. —Illustrating characteristic forms and outlines of mature mountains.

with Fig. 295 representing the Sierra type. And we are apt, as stated, to find these mountains composed of massive rocks, of schists, gneisses, granites, etc., rather than of the limestones, sandstones, shales and lavas, of ranges in the youthful stage.

There appears to be no well-recognized name for mountains of this kind equivalent to Sierra; they are variously termed mature, subdued, or old mountains. Examples of them are to be seen in the mountain groups and ranges of New England and eastern Canada, such as the Green Mountains, the White Mountains, and the Laurentides of Quebec, while in Europe the Black Forest region in Baden, and the old mountains of Scotland and Norway are illustrative of them. The Appalachians may also be considered of this nature, but along with some of the others mentioned, certain events, which we shall learn of later, have happened to them, which makes their history a complex one.

Final Stage: Peneplanation. — Ultimately, provided that no new upwarping movements occur, the mountains will entirely disappear and the region which they occupied will be reduced to base-level. See page 65. Since, however, the process of erosion goes on more and more slowly as the slopes lessen, it would evidently require an enormous lapse of time to actually base-level a mountainous tract, and we have no proof that this has ever actually occurred. But we

know in some cases such areas have been reduced to a relatively low, almost featureless country, in other words to a *peneplain*. Such a country may still be diversified by an occasional hill projecting above the general level, a residual of erosion, which, on account of the more resistant nature of the rock composing it, or possibly its originally greater size, has not been reduced like its neighbors. Such elevations, projecting above the surface of a peneplain have been termed *monadnocks*, by Davis, from Mount Monadnock in New Hampshire, which rises above the peneplain upland of central New England. An example is seen in Fig. 297.

Fig. 297. — Stone Mountain, De Kalb Co., Georgia. A residual monadnock, consisting of granite which rises above the surrounding plain of erosion. T. L. Watson, Geol. Surv. of Georgia.

Disregarding an occasional monadnock, we may say that when the peneplain stage is reached the mountains have been obliterated, but we may yet be able to recognize the fact of their former presence by the upturned and dislocated nature of the transversely eroded strata, by their frequent metamorphic condition, and by the slaty cleavage and faults which they exhibit, and by the frequent presence of stocks and bathyliths of granitic rocks intruded into them. We may not find the elevations, for, as LeConte has well said, "we find only the bones of the extinct mountains," but from these remains we may be able, in imagination, to reconstruct them. So, from the conditions of the rocks of southern New England, which is now only a hilly country, we are led to infer that it once presented the aspect of a mountainous region with lofty ranges running north and south through it.

Re-elevation: the Geological Cycle. — It must not be supposed that the life history of mountain ranges is necessarily a simple one consisting of a single period of compression, uplift, denudation, and extinction. On the contrary, the more they are studied the more evident it becomes that their history, in most cases, is much more complicated, and that the compressive orogenic forces have acted spasmodically with repeated times of uplift. When a much eroded range is again elevated, it may be said, as with rivers, see page 67, to be rejuvenated; the erosive agents must again set to work on their task of cutting it down. Thus a single period of uplift, and then of down cutting by erosion, may be considered a geological cycle, and examination shows that some ranges have passed through several such cycles. The Appalachians are an example which has been thoroughly studied. Originally they were formed, as has been stated, during the Permian period. They were then doubtless lofty mountains, but in succeeding time they were so greatly eroded that in the Cretaceous period the tract had been reduced to a peneplain, with only here and there occasional monadnocks rising above it. After this its surface was again domed by repeated upswellings and the revived rivers have carved it into its present condition.

It is through a recognition of such repeated cycles of rejuvenation and erosion that we are able to understand the problems presented by the topography and drainage of many regions. For example, we see that master streams have been able to maintain their courses during the time of re-elevation and have sawed their channels regardless of the underlying rock structure, so that they are now cutting through ridges and across the strike of the strata over hard and soft beds alike, instead of having their courses determined along weak belts as we should naturally expect, see page 69.

It has been often noticed that in many mountain ranges the summits rise to a remarkably uniform level, and the conclusion has often been drawn that such an accordance must represent the remains of a former peneplain. This appears to be carrying the idea of peneplanation to unnecessary and improbable lengths. For in the uprise of the area by folding and compression there would naturally be long stretches raised to the same general average height and consisting of about the same material. There would be, then, original accordance of height. Over a given region the action of the erosive agents would be approximately the same, and similar forces acting on similar material should give similar results. Moreover, since severity of erosion increases with the height, original inequalities would tend to disappear. Thus accordance of summit levels is what we should expect, not the reverse.

Some Results of Erosion in Folded Strata

Anticlines and Synclines. — The result of the erosion of mountain ranges, which commonly contain a variety of stratified rocks, folded and dislocated in different ways, and often igneous ones as well, is the

production of many kinds of topographic forms, dependent on the attitude of the beds and on the relative hardness, or resistance to erosion, which they exhibit. While some of these forms may be seen in regions of low relief, they are, as a rule, best studied as a phase in the history of mountain-making. One example is found in the erosion of anticlines and synclines. It would be natural to think

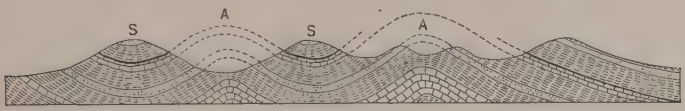


Fig. 298.— Illustrating anticlinal valleys and synclinal ridges.

that in a folded tract the anticlines would be ridges and the synclines valleys, and in young ranges this may, indeed, be the case, as in the Jura Mountains. But when maturely dissected ranges, such as the Appalachians, are studied it is very commonly found that, on the contrary, the valleys are cut in the crests of anticlines, while the ridges

Fig. 299. — Erosion of folded strata. North Beaver Creek, Bighorn Mountains, Wyo. N. H. Darton, U. S. Geol. Surv.

are the bottoms of synclines. In other words, the original topography, with respect to the structure, has been reversed. See Fig. 298. The student must, therefore, remember that anticlines and synclines are terms of *structure*, that, as previously explained, they do not necessarily denote forms of topographic relief.

The reason for this appears to consist primarily in that an anticline's crest tends to be under tension, that is to be stretched; consequently, the strata are apt to be thinned and cracked, producing a belt of weakness. The bottom of a syncline, on the contrary, is under compression, joints and cracks become closed, and

being thus strengthened, it can resist erosion better than the anticline. In the general lowering of the country by denudation the streams tend to carry away the anticlines faster, to seek out the weak belts, and to establish their valleys in them. See Fig. 299. If the beds consist of alternately hard and soft strata the effect will be more marked, because the hard stratum will be cut through first on the crest of the anticline, where it is highest and most exposed; the softer material below being reached, the erosion in it will be more pronounced than elsewhere. Thus, both by position and structure, the anticlines tend to be first worn away, and then to become valleys.

Parallel Ridges: Hogbacks. — As the erosion of folded strata composed of hard and soft beds proceeds and the hard beds are broken through on the anticlines, drainage ways tend to establish themselves along the belts of weak strata, as noted above. This gives rise to *longitudinal* valleys, following the strike of the beds, while the outcropping edges of the hard strata form the crests of the intervening ridges, as illustrated in Fig. 300, where several such

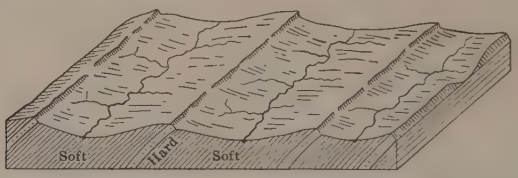


Fig. 300. — Illustrating the formation of longitudinal valleys of erosion and parallel ridges.

valleys on the side of an eroded anticline have been made. Parallel ridges of this nature are a characteristic feature over much of the eroded Appalachian mountain tract and are found in many other districts of disturbed strata. In the foothills of the Rocky Mountains' region where the level strata of the plains begin to show the initial foldings and displacements which culminate beyond in the ranges themselves, short eroded ridges or hills of this nature are very common and are popularly known as *hogbacks*. They may be several hundred feet high. An illustration of one is seen in Fig. 301.

In the erosion of a country with the structure seen in Fig. 300, the wear on the side of the valley which exposes the outcropping edge of the strata is more rapid than on the slope made of the backs of the beds. The whole system of drainage tends on this account to move in this direction, that is to the left, in the figure. There is evidently, then, a shifting, or as it is technically called a *migration*, of the divides between the valleys. If the structure is similar on both slopes of a divide, as for instance in horizontal beds of clay, then the erosion will be most rapid on the steeper slope, and the divide will migrate toward the gentler one, other conditions being equal. This movement of divides is constantly going on in a country undergoing erosion, its rapidity depending on the rate of the erosion, and in the struggle between divides new adjustments of drainage are constantly taking place. See Fig. 302. This fact furnishes the key to the solution of problems re-

Fig. 301. — A hogback, near Gallup, New Mexico. N. H. Darton, U. S. Geol. Surv.

Fig. 302. — View illustrating the development of topographic forms and drainage in inclined beds of hard and soft strata. Near Bisbee, Ariz. F. L. Ransome, U. S. Geol. Surv.

garding the origin of the varied features of topography which present themselves in many places.

Erosional Forms in Gently Inclined Strata. — Where disturbance of the sedimentary beds due to mountain-making dies away in the level-plains country the strata over wide areas may have a gentle angle of inclination. The same thing may occur also in the forming of a plateau, or in the faulting down of the masses of block mountains. In such cases, since strata are almost invariably composed of hard, strong, and more resistant layers alternating with soft, weak, less resistant ones, there results from erosion topographic forms composed of a long gentle slope on one side with an abrupt, or even precipitous, descent on the other. The long slope is maintained by the back, or upper face, of the resistant layer, while its thickness determines the height of the abrupt slope or cliff, as shown in Fig. 303.

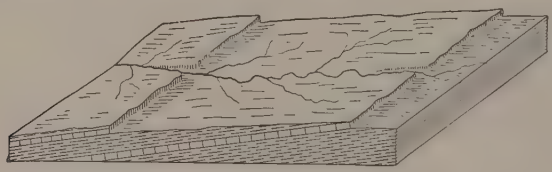


Fig. 303. — Diagram illustrating the formation of cuestas and escarpments.

Such an arrangement with long out-slope is known as a *cuesta* from the Spanish name for them in the southwest, and a cliff of this nature is often called an escarpment. Excellent examples of such cuestas are found in the region of the Rocky Mountains and, on a large scale, in the Colorado Plateau country. In some cases the hard stratum may be a sheet of lava. If the strata were horizontal the escarpment might through erosion extend entirely around it and we should then have a table-land, or mesa. See page 35.

CHAPTER XVI

ORE DEPOSITS

Definition of Ores. — The term *ore* is very widely used to designate anything that is mined from the earth for the uses of man. In a more strict and technical sense, however, it generally denotes those minerals from which *metals* are derived, and substances like coal, and salt, and stone or clay, which are used in their native condition are excluded. Hence, in thinking of ores we usually connect them with metals, and it is in this narrower sense that the term is used in this chapter.

Ores as Minerals. — Nearly all the different kinds of metals are made use of today, either as simple metals, or in some form of chemical compound. In addition, other substances, such as sulphur, phosphorus, etc., are mined and used. It is necessary, therefore, to enable us to study the occurrence and nature of ore deposits to choose a few of the more important types as examples and concentrate attention upon them; for this purpose, we may select the ores of *gold*, *silver*, *copper*, *lead*, and *iron*, and they will be chiefly used as examples. Of these five metals gold mostly occurs as the native metal. Silver and copper also occur in places as native metals, and important mining districts yield them in this condition. The metals are found also in combination with other elements as minerals, and lead and iron, as ores, occur only in this way. Thus silver occurs combined with sulphur, often associated with arsenic; copper is found combined with oxygen, as an oxide; with sulphur, as a sulphide, and also as a carbonate; lead occurs as a sulphide, as a carbonate, and as a sulphate; iron occurs as oxides, carbonate and sulphide, though this latter is not used as an ore of iron. There are, of course, other combinations in which the metals occur as minerals, but we are now speaking only of the most important ores. It should not be thought, however, that the metals and their ores only occur, and must be mined, separately; while this is true of iron ores, those of the other metals mentioned very commonly occur together, often in very intimate association, and such combined ores may be exploited for several metals. The facts mentioned above are shown in the little table below where they can be readily seen.

	Metal	Sulphide	Oxide	Carbonate	Sulphate
Gold	occurs	.....	.....	.....	.....
Silver	occurs	occurs	.....	.....	.....
Copper	occurs	occurs	occurs	occurs	.....
Lead	.....	occurs	.....	occurs	occurs
Iron	.....	occurs	occurs	occurs	.....

Gold occurs also in combination with tellurium, and both it and silver are found, often in very valuable quantities, in the ores of other metals, such as those of copper and lead, in a state of such minute particles that their exact condition is not known. Thus a large part of the silver is obtained from galena, an ore of lead, mentioned below. Silver also occurs combined with chlorine and with arsenic and antimony in combination with sulphur.

Important Ore Minerals. — The *properties* of the uncombined metals are so well known that they need no further mention. Reference to the table above shows that the chief forms of combination, in which the metals mentioned occur, are oxides, sulphides, carbonates and sulphate. Of these the sulphides, or sulphurets as they are sometimes called, are usually dark, heavy, opaque minerals with metallic looking appearance and luster. The oxides are in some cases metallic looking, but often less metallic appearing and even earthy. The carbonates and sulphates are not metallic in appearance but white or colored. Some of the chief minerals which compose these ores are found in the list below and a brief description of them will be found in appendix A.

List of Illustrative Ore Minerals.

Silver.	Argentite,	Ag_2S
Copper.	Chalcopyrite,	$CuFeS_2$
	Bornite,	Cu_3FeS_4
	Chalcocite,	Cu_2S
	Cuprite,	Cu_2O
	Malachite,	$CuCO_3Cu(OH)_2$
	Azurite,	$(CuCO_3)_2Cu(OH)_2$
Lead.	Galena,	PbS
	Cerussite,	$PbCO_3$
	Anglesite,	$PbSO_4$
Iron.	Magnetite,	Fe_3O_4
	Hematite,	FeO
	Limonite,	$2\,Fe_2O_3.3H_2O$
	Siderite,	$FeCO_3$.

This list is merely illustrative of the important ores; there are many other minerals which at times and in places may also become valuable sources of these metals.

Oxidized and Unoxidized Minerals. — Inspection of the list above shows that the ore minerals may be divided into two classes,

native metals and sulphides which contain no oxygen, and oxides (and hydrated oxides) carbonates and sulphates which do. These ores may thus be separated into oxidized and unoxidized groups. It has been previously shown, page 317, that there is a zone which reaches from the surface down to the level of ground water, in which the rocks and their contents are acted upon by the agencies of weathering, and that this is a region of change and oxidation of the outer shell. Below this the presence of the ground water excludes the air and the changes which go on are those of a chemical nature produced by the water itself and by the substances which it may hold in solution and deposit. Experience in mining teaches that in the upper zone the ores are most likely to occur as carbonates, sulphates and hydrated oxides; below this, they occur chiefly as sulphides, and in the case of iron as non-hydrated oxides, while metallic silver and copper may be also produced by the oxidation and alteration. The natural conclusion is that the ores were originally sulphides and have been changed by atmospheric agencies into the oxydized minerals and metals we now find in the upper zone. The importance of this fact in understanding properly the nature of ore deposits will appear later.

Native metals are found both above and below the level of ground-water. This seems to depend in the case of gold on its chemical capacity to withstand the action of the atmosphere in producing oxidation. Whether the copper and silver were originally deposited in the rocks as native metals is a point that will be considered later.

Mode of Occurrence of Ores. — The ore-minerals may occur in a great variety of ways. In one, for example, like magnetite, the oxide of iron, they are sometimes thinly scattered through a mass of rock in small particles, and the occurrence may be valueless because so large an amount of material must be mined and treated to secure a relatively small amount of metal that its value would not pay for the operation. Where fine particles of gold, however, are disseminated through rock or gravel, the great value of the metal may render the working of such a deposit extremely profitable. In most cases where ore occurs in a profitable quantity the mineral has been segregated, or the place enriched with it, to such an extent that a definite ore deposit has been formed, and the modes of occurrence of such ore deposits are of many different kinds depending on a great variety of causes and circumstances. Thus the ore may occur filling fissures or seams in the rock and thus forming veins; it may be found filling cavities of various shapes and of differing origins; or it may be in

the nature of beds or lenses lying between sedimentary strata, as is so often the case with iron ores.

Volume of Ore: Associated Minerals. — It must not be supposed that ore generally is found in a solid mass filling a cavity in the rocks. It is true that such occurrences have been known in special cases or for limited distances, but they are rare, and in the great majority of deposits the ore forms only a part, and often only a very small part, of the material filling the cavity or making up the vein. With gold the actual volume of the metal is only a minute fraction of the material which composes the vein, and which is yet termed "ore" and mined for the great value of this relatively minute gold content.

On the other hand, the fact that iron is used in great quantities indicates that its value as a metal must be small compared with gold and iron ore must, therefore, be relatively abundant and occur in large volumes.

It is evident, then, that ore deposits filling cavities, fissures, etc., consist of two things, metalliferous minerals or "ore" proper and associated substances which are known as "*gangue*," an old mining term. While gangue may be composed of many minerals, in most cases it is formed of very common substances or a mixture of them, the chief ones being *quartz*, (silica), and carbonates, such as *calcite* (carbonate of lime), *dolomite* (carbonate of lime and magnesia), *siderite* (carbonate of iron); less commonly, perhaps, *barite* (sulphate of barium) and *fluorite* (fluoride of lime) and sometimes rhodonite and rhodochrosite (silicate and carbonate of manganese). Where oxidation of the ore deposits has not been complete there is also apt to be associated with the ores sulphide of iron, *iron-pyrites* or *pyrite* (FeS_2). This may occur at times in large amounts and its presence in the rocks is rather indicative of mineralization. It is not used as an ore of iron, but is mined in some places for the sulphur it contains.

Other gangue minerals might be mentioned, but the above will serve as examples, and descriptions of them will be found in Appendix I.

Classification of Ore Deposits

Introductory. — In the foregoing paragraphs some general introductory statements concerning ores and their occurrence have been given and it is now necessary to consider the classification of them.

At the outset, we can divide them into two great classes, which we may call *primary* and *secondary*, in the sense that the primary ones are now found in the position in which they were originally deposited in bed-rock, while the secondary ones have been clearly shifted from their previous to their present position by some agency, or set of

agencies, and are thus products of disintegration. Thus, if we find particles of a metalliferous mineral as part of the structure of a fresh unchanged igneous rock it is natural to suppose that the ore is in its original place of formation, and to call it primary, while on the other hand, when we see grains of gold mingled with the sand and gravel of a stream bed, it is equally natural to infer that it has been shifted from its original position and that, consequently, it is a secondary deposit. We shall consider first the primary ones.

Primary or Bed-rock Ore Deposits

Division into Families. — The primary class of ores, deposited in their present positions, may be subdivided into two families depending on their relation to the rocks which enclose them. In the first, the method of occurrence shows us that both the ores and the rocks have been formed at the same time, they are contemporaneous; in the second, it is evident from the structure that the rocks were formed first and that subsequently by some agency the ores were deposited in cavities of one kind or another in these rocks. The first we may then term *contemporaneous* ore deposits, the second *subsequent* ore deposits; they are also called respectively *syngenetic* and *epigenetic*, from the Greek, meaning in the one case "born with" and in the other "born upon."

Contemporaneous, or Syngenetic, Deposits. — Cases where the ores have been formed at the same time as the rocks which include them fall into two groups, depending on whether these rocks are *igneous* or *sedimentary* in origin. In the first case, the masses of metalliferous substance, like the component mineral grains of the rocks, have been made by the cooling and crystallization of a molten igneous magma, as previously explained under the discussion on pages 305 and 306. They are, therefore, to be regarded as a *phase of igneous rocks* and we shall term them *type A* of ore deposits.

In the second case, the ores have been laid down from water as precipitates in the same way that the sedimentary beds have been formed, and just as the sediments are sometimes chemically (limestones) and sometimes mechanically (sandstones) deposited, so also are the ores. The contemporaneous ores made in this way we may call *sedimentary ore deposits*, and they form type *B*. The most important examples of these are to be found in certain iron-ore beds, whose mode of formation has been already discussed. See page 170.

Subsequent, or Epigenetic, Deposits. — In those cases where it is clear that the ore bodies are later than the rocks that enclose them we have learned from a great mass of evidence, part of it direct but

most of it indirect, that the metalliferous substances have been deposited from solutions. We infer also that in the great majority of these cases the solutions were hot, often so hot that they were either actually or potentially in the gaseous condition. Either in the form of hot solutions or vapors the ores were brought and deposited; the probable origin of these solutions, or vapors, is discussed later in an appropriate place.

If we consider the possible ways that a fluid carrying substances in solution and moving about in the rocks might be able to deposit its burden two methods suggest themselves, depending on whether there are, *a*, existent free cavities of some size in which it moves or, *b*, whether the rocks are nearly compact and the fluid is compelled to find its way through minute capillary openings, or by dissolving rock-particles to produce such openings, or a combination of both.

a. 1. Fissure Veins. — In the former case, *a*, we know from what has been previously stated (see page 333) that the rocks forming the outer layer of the earth's shell are much shattered and filled with fissures; we have seen how the ground-water moves in these fissures, and in a similar way, the hot fluids carrying ores in solution may also circulate. But such solutions, standing or moving in the fissure cavities, are in contact with their walls, and it is easy to imagine that they may become cooled, and deposit more or less of their burden upon the walls, since cooling in general lessens the capacity of liquids to carry substances in solution. Or, they may react chemically with the rocks with which they come in contact and thus have their chemical composition changed and, simultaneously with this, their ability to hold the mineral substances in solution, the latter being, therefore, deposited. We can imagine, for instance, that the solutions are acid, and that coming in contact with limestone they would be neutralized, with the formation of lime salts and the deposit of the metalliferous substances. Or again, it is quite possible to conceive that cooling and chemical reaction may be working together to cause the ore deposit, and that from the operation of both factors, it would form all the more rapidly.

Such deposits naturally take the form of films, sheets, or crusts deposited upon the walls of the fissure, which may be partially or wholly filled by the successive sheets of deposited substances. Usually it is not ore alone that forms the filling, but a mixture of this with a greater or lesser quantity of other minerals, such as quartz, calcite, barite, and the other gangue minerals previously alluded to. It is, indeed, common to find quartz veins in the rocks without ore-minerals in them.

Such ore deposits are known as *fissure-veins* and they are one of the most important kinds of deposits, being one of the chief sources of gold, silver, copper and other metals. See Fig. 304.

Fig. 304. — Gold-quartz vein; the mining discloses the width of the vein and the wall-rock on either side. Cook Mine, Central City, Colo.

a 2. Cavity-filled Deposits. — While fissures are undoubtedly the most common form of opening in the rocks and the ore deposits in them are of so great importance that they may be considered as a

kind by themselves, they are not the only shape in which cavities exist. The rocks are penetrated by cracks, crevices and jointing planes, and on a more minute scale there are the pore spaces between rock grains and, though of lesser importance, there are openings and cavities in soluble rocks, especially limestone, which have been dissolved out by circulating fluids, chiefly water containing carbonic acid. Such cavities may become the channel-ways, or receptacles, of ore-bearing solutions and, as in the case of fissures, have ore bodies deposited in them by a similar set of processes. We may place them in one general group and term them, *cavity-filled ore deposits.*

b, Replacement Deposits. — In the cases just discussed, we have considered that the opening or cavity has been already produced by a previous process before it becomes the receptacle of the ore-bearing solution and its deposits. As previously suggested, however, it is quite possible that the production of the cavity or cavities, by the solvent action of an ore-bearing solution and the deposit of mineral substances may be a simultaneous one. There may be rock-particles which are chemically affected by the solution, whose activity as a chemical reagent may be greatly enhanced by its heated condition. In measure as the mineral grains of the rock are dissolved, so molecule by molecule they may be replaced by a deposit of ore-mineral in the exchange of substance. Thus by a chemical replacement of the whole, or a part of its contents, more or less of a rock area may give place to a mass of ore, or become so enriched in metalliferous grains through its substance, as to form a valuable ore deposit. In allusion to its mode of formation we may term this a *replacement ore deposit.*

It is evident that between cavity-filled and replacement ore deposits no sharp line can be drawn; all degrees of gradation between them must exist. Yet at either end of this line of gradation each type stands clearly forth, and definite examples of them can be readily recognized by the experienced observer. It is, therefore, not only a matter of convenience, but of scientific value that the types should be recognized, especially in classification. This gradation of the various kinds of ore deposits is not confined to these two, but is more or less true of all the various kinds, and this fact is discussed later.

Replacement deposits may be divided into two different types, according to the nature of the processes which have acted upon the rock minerals and replaced them with ore. In the first case this has been done by the ordinary normal circulating waters in the upper zone of the earth's crust; these are of lesser importance. In the second they have been made by the heated solutions given off by masses of magma intruded into the rocks in the varied forms of stocks,

dikes, sheets, etc., as detailed in Chapter XII, during their period of cooling and crystallizing into igneous rock. As we have previously learned, page 329, the effect produced on the enclosing rocks by igneous intrusion is known as contact metamorphism, and since the deposition of ores is one of these effects and the deposits are characteristically found in the zone of changed rocks, they may be appropriately termed *contact metamorphic ore deposits*. They are of great importance and further details regarding them will be given later.

Summary of Primary Deposits. — The discussion which has been given in the preceding sections in which the different kinds of primary ore deposits have been briefly set forth may now be summarized in tabular form as shown below.

TABLE OF PRIMARY ORE DEPOSITS

Primary Ores, those formed in the place where they now exist.

Contemporaneous (Syngenetic) made at same time as enclosing Rocks.	1. As a Phase of the Crystallization of *Igneous* Rocks. (*A*) 2. Deposited as Sediments with *Sedimentary* Rocks. (*B*)
Subsequent (Epigenetic). Later in Origin than the enclosing Rocks.	*a*. *Pre-existent* Cavities filled by deposits from ore-bearing Solutions. 1. Cavities have the Form of Fissures; producing *Fissure Veins*. (*C*) 2. Cavities have some other Form making *Cavity-filled Deposits*. (*D*) *b*. Formation of Cavity and Deposit of Ore simultaneous by *Chemical Replacement* of Rock-mineral. (*E*) 1. By normal processes of circulating waters. 2. By contact metamorphism.

Secondary Ore Deposits

Introductory: Definition. — It has previously been shown in this volume that the rocks of the outer layer of the earth's crust are subject to many agents which tend to change and even to destroy them. Partly these agents are mechanical in their nature and partly they are chemical in action. Under the weathering of rocks, the formation of soil, and erosion, their activities have been discussed, and the results have been pointed out in the descriptions of the chemical work of underground water and of the formation of stratified rocks.

But in the same way as the rocks are subject to these agencies so also are the ore deposits contained in them. The primary ores, described

in the preceding sections, are likewise subjected to the chemical activities of the air and its contained gases and to those of the circulating ground-waters, as well as to the mechanical effects of frosts and moving waters. They tend to change chemically, to be oxidized, to pass from sulphides, for example, into hydrated oxides, carbonates, sulphates, etc., as mentioned in a previous section, and, after such changes or during the process, either to go into solution and be carried away, or to be broken up and transported elsewhere. If taken in solution they may be carried into the ocean and added to that great ultimate reservoir of soluble materials and thus, in a sense, to be lost; but on their way, under proper conditions, they may be again deposited in some place and thus give rise to renewed and even concentrated ore deposits. Or, if transported mechanically, they may through natural causes be concentrated in some particular place and thus again form a valuable deposit of metals, or their ores.

All such deposits of which there is clear evidence that they have been *moved* from their original position to the ones which they now occupy and of having thus been shifted by some set of processes are termed *secondary ore deposits*.

Kinds of Secondary Deposits: Chemical, Mechanical. — In contrast with the primary ore deposits the secondary ones require only a very simple classification and may be divided into two groups, which, as foreshadowed in the previous paragraphs, depend upon whether they have been *chemically*, or *mechanically* moved and concentrated.

In the *chemically concentrated ore deposits* the most important cases are those where the ores have not been moved any great distance, but chiefly from upper to lower levels of the deposits themselves. By this process of solution, transfer and redeposition, a concentration of ores may occur which produces, in the midst of what would otherwise be a lean deposit of little worth, areas of great richness and value. Such places may be called *enrichment zones*, and as they are of great importance in mining operations, they are more fully treated in a following section.

The *mechanically concentrated ore deposits* represent those cases where the rocks or mineral substances surrounding the ores or metallic particles have been acted upon by weathering and erosion and carried away, leaving them behind. This presupposes that the ores are not changed in such a way as to be taken into solution and removed; if mechanically changed, they must remain in some insoluble form. They are also usually heavier than the soil particles and their greater specific gravity either causes them to remain and gradually accumu-

late on the site of the deposit, or, if carried away by stream action, to accumulate in particular places and thus form workable deposits. The breaking down of quartz veins containing specks of metallic gold and the accumulation of the latter in the sands and gravels of stream-beds is an illustration of this.

General Classification

The brief descriptions of the different kinds of ore deposits which have been given in the preceding pages may now be summarized in the form of a table which will serve to show their classification.

TABLE SHOWING CLASSIFICATION OF ORE DEPOSITS

Class	Period of formation	Mode of Origin	Name
Primary: Deposited in their present position.	*Contemporaneous* (with enclosing rocks), Syngenetic.	Phase of *Igneous* Rocks.	*A. Igneous* Ore deposits.
		Deposited as *Sediments.*	*B. Sedimentary* Ore deposits.
	Subsequent (later in origin than enclosing rocks), Epigenetic.	Filling of *existent* cavities by ore-bearing solutions.	*C. Fissure Vein* Ore deposits.
			D. Cavity-filled Ore deposits.
		Chemical replacement of minerals in rocks by ores in solutions, (or gases).	*E. Replacement* Ore deposits. 1. Normal. 2. Contact-metamorphic.
Secondary: Changed from their previous to their present position by some agency	*Moved.* Ore deposits, originally of foregoing kinds, acted upon by various processes and shifted in position, thus later.	*Chemical* solution, and concentration by redeposition.	*F. Chemically Concentrated* Ore deposits (enrichment zones).
		Mechanical breaking down, transport and concentration of ores.	*G. Mechanically-concentrated* ore deposits, (Placers).

The above classification is based upon clearly defined and definite types of ore deposits, and also upon theoretical considerations. But it must not be supposed by the student that all ore deposits belong very sharply or clearly in one or the other of the above divisions. It is true that a great number do, but many, perhaps the majority, exhibit a commingling of these types to a greater, or lesser, degree. Thus, in a fissure vein belonging to the primary class there may be an

enrichment zone of the secondary class, and the deposit is thus partly primary and partly secondary. Or again, iron ores deposited as beds in the sedimentary strata are for the sake of convenience considered as primary, just as it is convenient to consider the stratified rocks as a primary division of all the rocks, although they have moved from their original place of formation.

By inspection of the last column in the table it will be seen that there are seven important types of ore deposits, and we may now state their more important features with illustrative examples.

Important Characters and Examples of Ore Deposits

A. **Igneous Ore Deposits.** — In the chapters devoted to volcanic action and igneous rocks it has been shown that when the magmas, the molten fluids of the earth, solidify into rocks they generally undergo a process of crystallization so that the resultant mass consists of interlocked mineral grains. Mingled with the more important constituents are more or less intersprinkled grains of magnetite, or some other ore of iron. It is conceivable that during the process of crystallization, through movements in the fluid mass, and owing to other causes not yet fully understood, the grains of iron ore might be largely concentrated in certain places in a rock-body and give rise to workable deposits.

It is held that this is the origin of some iron ores, as in Sweden, which have been worked. It is also thought by many that some copper deposits have been made in this way, the copper being associated with iron and sulphur in the mineral called chalcopyrite. But while these, and some other things of importance mentioned below, may occur in igneous rocks, the ore deposits of this kind, when considered in relation to the other ways in which ores are found, are really of minor importance.

In most cases where iron ore occurs concentrated in a rock mass the iron and oxygen are apt to be associated with the semi-metal titanium in the mineral called *ilmenite* ($FeTiO_3$) mingled in grains with magnetite (Fe_3O_4). Until recently, owing to the infusibility of ilmenite and the presence of the titanium, no economical method for the smelting and extraction of the iron from such ores had been found; now electro-magnetic methods of separation of the pure iron ore from ilmenite are beginning to be used. Large bodies of such titanic iron ore, as it is often called, are known to exist in Norway, Canada, the Adirondacks and other places, and their utilization will probably come in the future.

Among the igneous ore deposits may be mentioned those of nickel and chromium, metals used for various purposes; these occur in segregated minerals in certain igneous rocks or in the products of their decay. Platinum and the diamond also originate in certain igneous rocks; the diamond mines of South Africa being in the decayed rock filling old volcanic necks. See remarks on peridotite, page 312.

B. **Sedimentary Ore Deposits.** — The most important examples of these are the iron ores which are found as layers or huge flattened lenses in the sedimentary strata, as previously mentioned. Their mode of formation has been rather fully discussed in Chapter VII, page 170, and from what is there stated it may be inferred that these ores are chemical precipitates, sediments made by the action of bacterial life. It is possible also to consider that in some cases they may have been precipitated by simple chemical reactions without the aid of life. Or again, it is conceivable that in the breaking up and erosion of the original rocks the iron-ore particles were not removed by solution but carried away as mechanical sediments, like other soil particles, and by virtue of their higher specific gravity were concentrated in particular places, thus forming the deposit. In this case they are mechanical in origin. Iron-ore deposits are often of vast size, covering hundreds of square miles, or more. A good example of them is seen in the great beds of "Clinton" ore which stretch from New York State to Alabama, and which are further considered in an appropriate place in the second part of this volume.

The position of such beds depends on that of the associated strata; if flat or inclined or folded, so are the included ore-beds. Originally the ores were probably hydroxides (limonite) or carbonate (siderite). But it may have happened that the region has been subjected to orogenic forces, to folding and to metamorphism. Then, not only the stratified rocks, but also the contained ore-beds will be metamorphosed and changed; like the rocks they may become hard and crystalline, lose water or carbonic acid, and become anhydrous oxides (hematite and magnetite). Also intrusions of igneous rock in the vicinity of the ore-beds may produce local metamorphic effects, and act in other ways as well. Thus, the character of an originally simple deposit may become much complicated and its origin obscured. The great iron-ore deposits of the Lake Superior Region afford a striking example of this. They appear to have been laid down as chemical sediments, but have since suffered from regional and contact metamorphism, and from chemical solutions which have more or less moved and concentrated them. They are thus of complex origin and afford a good example of the commingling of types previously mentioned.

C. **Fissure Veins.** — In a previous section it has been shown that solutions carrying ores may deposit them in fissures and cracks in the rocks, and that these form one of the most important kinds of ore deposits. The reason for this is easily seen when we reflect that cracks and fissures are the most abundant and natural form of openings or cavities in the outer rocky layer in which the fluids can circulate. The thickness, depth, and extension of such veins, like the fissures which they fill, are very variable features; they may be only a few inches (Fig. 305), or many feet and even yards in thickness;

veins have been followed downward several thousand feet before increasing difficulties caused an abandonment of the working; they may extend only a few hundreds of feet, or many miles. As with dikes, it is natural to think of a vein as a vertical sheet or wall traversing the rocks, so the same terms are used to define its position and departure from the vertical, see page 296; we speak, therefore, of its *trend* and *hade*. The same terms are also used, it will be recalled, page 338, with respect to fissures and especially fault fissures, which naturally have a close connection with veins. Very often, bearing in mind the resemblance to inclined strata, which are referred to the horizontal instead of the vertical, the terms *dip* and *strike* are used instead of hade and trend; this is the more common usage in America. And again, recalling what was said with respect to fault fissures, page 338, we speak of the upper contact of a vein with the enclosing rocks as the *hanging-wall*, the lower one as the *foot-wall*.

Fig. 305. — View of a small fissure vein, two inches wide. The containing wall-rock is seen on either side, beyond the narrow dark line. One-half natural size.

As previously mentioned, the ore is usually only a portion of the materials composing the vein; the proportion between ore and the gangue minerals is a very variable one, not only between different veins, but in different parts of the same vein, and this forms one of the uncertainties of mining operations. The variation in a vertical direction may be original, or it may be a secondary effect, as explained later under alteration and enrichment zones. There may also be great variations in the horizontal direction or extension of the vein, dependent upon several factors; such as a change in the nature of the country rock, which would affect the chemical reactions that caused the solution to

deposit the ore; or by the contact with a cross-cutting body of igneous rock, whose advent stimulated the activity of the ore-bearing fluids; or by the crossing of another vein.

It has been pointed out that a fluid-depositing material in a fissure would naturally do so by forming coatings, crusts, or films upon the walls. Each wall would receive a layer, and as the composition of the moving liquids changes from time to time, so the nature of the layers would change, one of gangue mineral being succeeded by one of ore, and this perhaps repeated several times, as illustrated in Fig. 305. The section of such a vein may thus exhibit a banded appearance which is known as the *ribbon-structure*. The fissure may be tightly and compactly filled with the ore, or it may happen that the last coatings do not completely fill it; in this case there are usually flattened lenticular cavities lined with crystals from the last deposition separating the latest deposited crusts; these are termed *vugs*. See Fig. 306. Often the actual vein is separated from the country-rock by a thin layer of decomposed rock or clay, or other minerals, known as the *selvage*, which coats the contact.

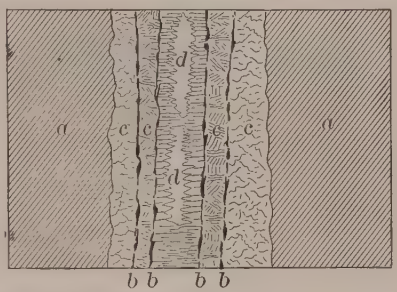


Fig. 306. — Section of a fissure vein; *aa*, wall-rock; *bb*, layers of ore; *cc*, gangue; *d*, open cavity or vug, lined with crystals.

The irregularities of veins are very great. They may widen, giving rise to chambers of ore, which when very great have been called *bonanzas*, or they may *pinch* until only thin films or stringers are left to show their continuation, to again widen beyond, or finally end. They may twist or turn in their course, branch, and perhaps re-unite, send out stringers into the surrounding rocks, be cut by other veins or by dikes. Or again, masses of country-rock, known as *horses*, may be encountered in the vein, or a major vein may be composed of a number of closely parallel minor ones, or finally, the vein may represent merely a shattered zone of rock whose interstices are filled by interlacing films of ore and gangue. Thus countless variations from the simple type occur, depending on the nature of the water ways through which the solutions passed. Veins are frequently cut by faults with greater or lesser amounts of displacement, a fact which forms one of the most serious problems of mining operations. All that was said about faults in the discussion of them in Chapter XIV may be here considered with profit.

One of the most interesting and important examples of fissure veins is found in those which have furnished so large a proportion of the world's supply of gold. The vein typically consists of massive white quartz through which is scattered more or less yellowish masses of iron-pyrites. The gold forms only a minute part of the whole and is seen, as a rule, only in occasional tiny specks of the native metal; it may be mostly concealed in the pyrites. Veins of this nature are found

in many parts of the world, some of the most noted being in California and other parts of the North American Cordillera. Not only gold, but silver and copper ores and those of many other metals are found in veins, usually with certain associations of minerals that accompany them; as copper and silver ores in the Butte district of Montana, and ores of silver, cobalt, etc., in the veins at Cobalt, Ontario.

The probable origin of fissure-vein ore deposits will be considered later, after the next and closely related kinds have been described.

D, E. **Cavity Fillings and Replacement Deposits.** — It has been previously pointed out that no sharp line can be drawn between these two classes of deposits, for it is obvious that in some cases it must be very difficult, if not impossible, to determine whether a cavity previously existed, or was made by the ore-bearing solution eating away the rock and leaving the ore in its place. In a typical cavity filling, we conceive the ore deposited in some existent channel-way or opening made in the rock, see Fig. 307; in a typical replacement deposit,

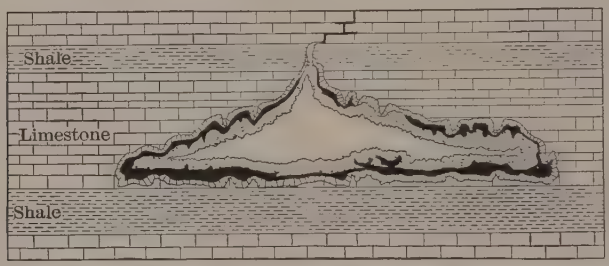


Fig. 307. — Cavity-filled Deposit. Shows an open cavity coated by deposited layers of gangue and ore, the latter, black. The stalactites and stalagmites of the original opening show the cavity existed before the deposition. Masses of ore fell from the roof before the last deposit was made.

we conceive a porous rock penetrated by the ore-bearing solution and an exchange, molecule by molecule, of rock substance and ore. See Fig. 308. An example of the latter would be the effect of an acid solution of copper sulphate upon limestone, by which copper carbonate is deposited and sulphate of lime (gypsum) is carried off, thus $CuSO_4 + CaCO_3 = CuCO_3 + CaSO_4$.

The equation given above represents the chemical exchange in simple terms; in reality it would be much more complicated in the supposed case.

One of the most important examples of ore deposits of this nature is found in the silver-lead ores which in Colorado, Montana, Idaho and other parts of the Rocky Mountains region have furnished such great quantities of metals and whose exploitation has done so much toward the development of the western states. In these cavity-fillings, the ore-bodies may be of extremely irregular shapes and sizes. Often they are long and rudely cylindrical in form and are termed *chutes*, or chimneys of ore. At other times they may take the character of flat-

tened lenses lying between strata; as in the lead and zinc ores of the Mississippi valley. They are sometimes of great size.

Origin of Epigenetic Ore Deposits. — In fissure veins, cavity fillings and replacements it is quite clear, and generally agreed to, that the ores have been deposited by solutions, but in regard to the origin of these solutions widely different views have been held. They may, however, for practical purposes be reduced to two main theories, which we can discuss under headings *A*, *descending* solutions, and *B*, *ascending* solutions.

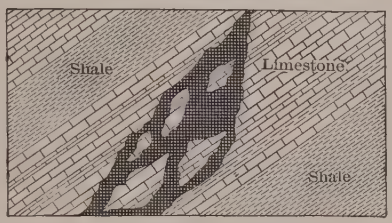


Fig. 308. — Replacement ore deposit. The dark area, ore. The suspended blocks of still unaltered limestone in the ore body show the cavity could not have been an open one when the ore was deposited.

A. According to this view, the material has been brought into the cavities by the action of descending surface waters which have leached the ore-materials out of the overlying rocks, and concentrated them in favorable places in veins, etc. A modification of this regards the fluids as circulating in the rocks and depositing the ores taken from them on the adjacent walls of the fissure and has been termed the "lateral secretion" hypothesis. The idea is essentially the same as that of descending solutions except that the movement is chiefly sidewise, instead of vertical. This hypothesis as an explanation of the absolute origin of primary ore deposits no longer enjoys the favor that it once held and has been largely supplanted by *B*, described below.

Some small deposits have undoubtedly been made in this way, such as veins of nickel ore in the serpentine rocks, iron-ore veins in ferromagnesian rocks, etc., but the hypothesis does not appear adequate to explain the great ore-veins for many reasons, some of which are as follows. To produce such ore deposits by leaching, an enormous amount of rock would have to be altered, but there is no evidence of this and, on the contrary, large veins of ore are not infrequently found traversing perfectly fresh, unchanged rocks. The best ores are often found in rocks which contain no traces of the elements composing the ores, such as zinc ores in limestone. We should expect also that descending waters would deposit oxidized materials, such as carbonates, quartz, sulphates, etc., whereas the ores in their primary condition are largely unoxidized. We should not expect the irregular disposition of the ores in the veins, according to this view, nor can we understand why a change in the enclosing country-rock from one certain kind to another should in one place cause a change in the contents of the ore-vein and not at another. Nor can we understand why in a given rock mass, such as a body of granite, there could be different sets of veins, each set with its own peculiar ores. It is facts of this kind, and others, which have led to the discarding of the descensional hypothesis as a final explanation of the origin of epigenetic ores.

B. The alternative view regards the solutions as *ascending* ones and ascribes to these solutions a magmatic origin. It will be recalled that under volcanic action, under hot-springs, and under the discussion of igneous rocks, the existence of volatile constituents in the earth's magmas has been repeatedly pointed out and that, as the magmas rise into the outermost shell of the crust through changes of stress and other causes, these volatile components escape through loss of pressure, or are excluded in the process of crystallization and solidification. We must imagine that originally they are in the gaseous condition as they leave the magmas, but through cooling and accumulated pressure they may pass into the liquid state, or meeting descending waters, they may heat and charge these with the substances of which they are composed. Among these latter are the various acid gases, which have been mentioned under volcanoes, water-vapor, silica, and other compounds, and especially the metallic elements which give rise to the ores. It should be conceived that after the intrusion of a body of igneous rock there comes a period, attending and following its solidification, when these volatile compounds are passing off through fissures and openings in the rock-body itself and in the surrounding and covering masses of rock, and are producing an active circulation in them of heated solutions; it is at this period, known as the "pneumatolytic" or gas forming stage, and from these solutions, that the ores are deposited. Obviously the truth of this view will depend very largely on the relation which can be traced between the occurrence of igneous rocks and that of the ore deposits.

Investigations of recent years show that this connection is in general a very close one. Thus tin ores are found only in bodies of intruded granitic rocks, granite and granite-porphyry, or in their immediate vicinity, and they are accompanied by minerals whose composition shows an origin due to volatile compounds. So, platinum is found only in connection with certain kinds of igneous rocks, such as gabbros and peridotites. Again the connection of certain gold ores, as at the Treadwell Mine in Alaska, at Cripple Creek, Colorado, and in the Judith Mountains, Montana, with the igneous rocks is a direct one, Fig. 309. In other cases, and generally, the ores are not found directly in the igneous rocks, but in those immediately in contact with them, and especially in limestones, suggesting that at a little distance the cooling of the solutions enabled them to deposit the ores and that the limestone would neutralize their acid condition and thus help toward the deposition.

That the immediate vicinity of igneous rocks, or the "contact zone" is the most favorable place to search for ore deposits is a fact known even to the rudest prospector, who is always seeking for a "contact of porphyry and lime." The rich silver-lead ores, and many of copper and of gold, in the region of the Rocky Mountains show this unmistakable connection with intruded igneous rocks.

In folded regions faults are liable to form along the sides of previous massive intrusions and such fissures may give rise to later injections, or in places to fissure veins, such as the gold-quartz veins of California and other regions. Sometimes the direct relation with igneous rocks cannot be seen, but must be suspected, as in the lead-zinc ores of Missouri and other places in the Mississippi valley. That these were made by ascending solutions is indicated by the dissimilar properties of the ores in different districts, the variable relations between lead, zinc and copper, the occurrence of barium, nickel, and cobalt, and in places of calcium fluoride, substances not normally found in stratified rocks. It may be true that these substances and ores are disseminated as particles through the rocks of this region, from which some have argued that the ores were precipitated from the ocean water in which the sediments were deposited and by later concentration have massed in the ore-bodies; but admitting the latter part of the process, such an original deposition seems abnormal in light of our present knowledge. Once given the idea that different bodies of magma contain the materials of the ore deposits, and in very variable proportions, and that these are given off during the "pneumatolytic" stage and pass into heated solutions which carry and deposit them, and the origin of epigenetic ore deposits becomes clear and understandable. Nor is it necessary that in all cases igneous rocks should show at the surface to prove this; the igneous material, not having attained the surface, may be yet buried below.

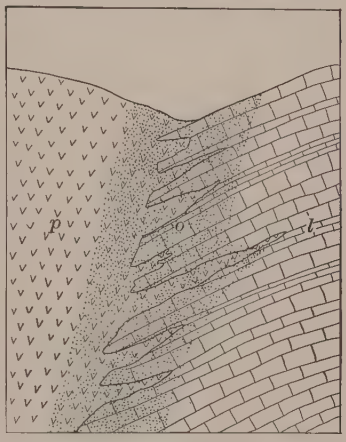


Fig. 309. — Diagram of a contact ore deposit; *p*, porphyry in contact with *l*, limestone. The zone of contact, *o*, has been affected by ascending solutions which have altered the rock and deposited telluride of gold in them. Judith Mts., Mont.

F. **Chemically Concentrated Ore Deposits.** — As has been previously mentioned, the most important of the cases where ores occur in profitable deposits through chemical concentration are in the so-called enrichment zones, found in connection with fissure veins, cavity fillings and the replacement bodies previously described. Since, however, the subject is also involved with the important one of the alteration of primary ore deposits by meteoric agencies, and such processes of alteration are not necessarily in all cases attended by movement and redeposition of the ore, it seems better to consider these processes and their results under the general heading of the alteration of ore deposits, which is done in a succeeding section.

G. **Mechanically Concentrated Ores: Placers.** — The method by which ores may be mechanically concentrated has been already explained, page 390, but a few words may be added to what has been given and some examples presented. Such a concentration could

take place in one of two ways; either the surrounding rock could be chemically dissolved and its substance carried off, leaving the ore to accumulate, or both the rock and ore could be mechanically broken up by erosion and the ore concentrated by virtue of its higher specific gravity. The first case occurs essentially with limestones, which as we have seen are soluble rocks, and in this way is explained the origin of certain deposits of iron and manganese oxides which furnish useful ores. The most striking examples of the latter are seen in the gold

Fig. 310. — View of a gold placer mine in operation. Banks of sand and gravel containing the fine gold particles are being washed down by powerful jets of water into sluices where the gold is caught in pockets of mercury. La Grange Mine, Northern California.

placers, or washings, where the gold, set free by the erosion agencies from the original veins in higher regions, is now in the sands and gravels of stream beds, as in California, Alaska and other places, from which it is obtained by hydraulic processes. See Fig. 310. The essence of such processes consists in removing by some means the barren portion of the material and passing the auriferous part through some contrivance which brings the gold in contact with mercury which absorbs it and from which it may be afterwards recovered.

Mechanically concentrated ores of this nature, among which may be mentioned gold, platinum, tin, iron and gems, such as the diamond, sapphire, etc., as well, constitute undoubtedly the most primitive kinds of ore deposits which were worked by man.

Alteration of Ore Deposits: Enrichment Zones. — Like the rocks which enclose it an ore deposit once formed is subject to alteration and by the same agencies of weathering and surface waters with their contained gases. Under normal conditions, we do not find, therefore, the upper portions of a metalliferous vein, down to the level of ground-

water, in the same state as that in which it was originally formed, but, on the contrary, with the metallic contents in a different set of mineral combinations and with a different arrangement. Whereas in the normal vein the metals may have been in combination with sulphur, as sulphides, and without oxygen, they are now carbonates, sulphates, or oxides, all oxidized forms, or possibly as simple native metals. We can, perhaps, understand this change best by the description and discussion of a particular case, selecting a rather simple one.

Let us imagine a copper vein, Fig. 311, consisting chiefly of quartz with intermixed masses of copper-iron-pyrites (chalcopyrite, $CuFeS_2$) as the ore, in its original, normal condition. The outcrop of such a vein on the surface shows merely as masses of cavernous rusty quartz, stained red to brown by oxide of iron. It may exhibit no trace of copper, the original ore having been completely destroyed by the action of the atmosphere and surface waters, the copper taken into solution and leached downward, while the iron is left as an insoluble colored oxide with the quartz. Such a rusty covering or capping of ore deposit is a very common one and is known to miners as *gossan*, or "iron hat." On following the vein downward, at a variable distance, copper ore is found, not the original unoxidized sulphide, but blue and green carbonates of copper; azurite, ($2\,CuCO_3 \cdot Cu(OH)_2$) and malachite, ($CuCO_3Cu(OH)_2$) and, usually, more or less increasing downward in amount. These carbonates are due to the destruction of the original ore, by the oxygen and carbonic acid of the atmosphere and surface water, to the copper having been taken into solution, leached downward, and deposited. This continues down till the level of ground-water is reached, which may in some cases be a distance of several hundred feet, whereupon a different condition of things will be found. Below this level, the ore is protected by the

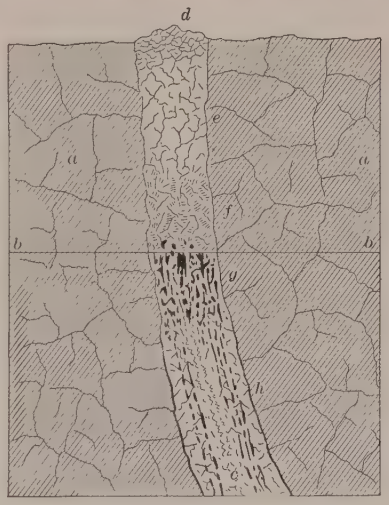


Fig. 311. — Diagram illustrating alteration of an ore-vein and a secondary enrichment zone; *aa*, country-rock; *bb*, level of ground-water; *cd*, ore-vein; *d*, capping of gossan; *e*, leached and barren part of vein; *f*, concentrated oxidized ore carbonates; *g*, secondary enrichment zone of highly metallic sulphides and metals; *h*, normal part of vein with unchanged, lower-metalled sulphides.

water from the oxidizing action of the atmosphere and the carbonates give place to sulphides. These sulphides are not, however, those of the original deposit, but others in which there is a much larger proportion of copper to sulphur. Thus the chalcopyrite, $CuFeS_2$, of the original deposit is replaced by *bornite*, Cu_3FeS_3, or *chalcocite*, Cu_2S, or even in part by metallic copper, Cu, thus showing the increase in the amount of the metal. This appears to be due to the leaching solutions, which carry the copper downward from the upper part of the vein, as mentioned above, and bring it below the level of ground-water and in contact with the original sulphide ore. Then, by chemical reactions the latter are changed into lower sulphides, containing a larger proportion of copper. Thus the portion of the vein at the level of ground-water, and for a variable distance beneath it, is much richer in the metal than the general average of the normal vein below. This is known as the *zone of secondary enrichment*, and below it the vein eventually assumes its normal unchanged character. See Fig. 311. This illustration will serve to explain the origin of division *F* of our table of classification, *secondary ore deposits*, in which the ores have been moved from their original position and *concentrated by redeposition by chemical processes*. The example has been selected for copper, but the process applies also to lead, silver and many other metals and to other forms of deposit as well as to veins.

Numberless variations of what has been described above are met in different places according to varying circumstances, such as the different forms of veins and deposits, the different kinds of metalliferous and other minerals they contain and the varied conditions to which they have been subjected, but it should be conceived as the normal process moving downward along the vein in proportion as the country is lowered by erosion. Not all of the metal leached down is necessarily redeposited, it may be largely, or even wholly carried away in solution and lost. The leaching solutions coming from the surface may be, as explained under the formation of iron ore page 161, reducing ones, which may convert the metals into the metallic state. Gold, which is not acted upon chemically by these solutions, is left in the rusty quartz of the oxidized part of the vein in the metallic condition, forming what is known as "free-milling" ore, from the ease with which it can be directly extracted by mercury, and in contrast to that in the unoxidized part where it is mostly enclosed in unaltered iron-sulphide (pyrites), which has to be concentrated and treated by special processes to obtain its content of gold.

In mountainous and northern regions, like parts of the Rocky Mountains, Canada, and Alaska, which have recently experienced severe glaciation, it may be found that along with the general erosion of the country the former oxidized portions of veins and other ore deposits have been ground off and carried away, bringing the unoxidized sulphides to the surface. The retreat of the ice may have been too recent to permit of the formation of a new zone of oxidation and the present surface line may pass through the former zone of secondary enrichment,

as appears to be the case at the silver-cobalt mines at Cobalt, Ontario, or it may even be below it, in which case no enrichment zone will be found as the vein is penetrated.

The facts which have been exposed above afford an explanation of the common view held by miners and prospectors that an ore-vein must grow richer in depth. Under usual circumstances with an oxidized vein this would be the case, until the zone of secondary enrichment is passed, when it will grow leaner in assuming its normal character, while, with unoxidized sulphides at the surface, as explained above, it will more probably grow poorer in ore. This may be readily understood by conceiving different surface lines passing through the vein shown in Fig. 311.

Metamorphism of Ore Deposits. — It has been previously stated that no hard and fast lines can be drawn between the different kinds of ore deposits, that the types established in our classification merge into one another, and that, therefore, while these types serve as useful center-points around which the different kinds may be grouped, intermediate varieties will be found between them. We have also seen that the deposits are subject to alteration and change of position by chemical agencies, which tend to change them from primary to secondary ores, and it is easy to conceive that such changes may be slight, very great, or even entire. But there is also another factor which may affect ore deposits and may add to the difficulties which arise in correctly interpreting their origin and in classifying them, and that is the agency of *metamorphism*. The subject of the metamorphism of *rocks* has been previously discussed, page 319, and it has been shown that both stratified and igneous ones may be converted into gneisses and schists, marble, quartzite, etc., and that such changes may be *general*, produced by compressional processes of folding, etc., over wide tracts of country, or *local*, as in the zones about intrusions of igneous rocks, or a combination of both. Thus, just as *rocks* may be metamorphosed, so also may be the *ore deposits* which they may contain. In consequence of this, their original nature may be much changed and their origin obscured. Perhaps some of the most striking examples of this fact are to be found in beds of iron ore, laid down concordantly with the strata as deposits of non-crystalline, more or less earthy limonite ($2\,Fe_2O_3\,.\,3\,H_2O$), or siderite, (carbonate of iron, $FeCO_3$), which by the agents of metamorphism attendant upon folding have lost their volatile constituents and become converted into hard, compact, more or less crystalline masses of hematite (Fe_2O_3), or magnetite (Fe_3O_4), often found in regions of metamorphic rocks. And other ores beside those of iron may be affected in a similar way.

Here, in part at least, may be placed the great iron ore deposits of the Lake Superior region. Originally sediments, perhaps chemical precipitates from bodies

of water, they have since been changed by chemical agencies and in places concentrated in the hollows of synclines by downward leaching and chemical replacements, and have been affected by the action of regional and local, or contact, metamorphism. Later erosion, especially that of the glacial period, has brought them to, or near, the surface and rendered them accessible to exploitation. The changes they have suffered render their interpretation one of the most difficult problems of economic geology.

PART II

HISTORICAL GEOLOGY

BY

CHARLES SCHUCHERT

CHAPTER XVII

MATTER AND ORGANISMS

Man, even though his body is large compared with the average size of living things, is after all but microscopic in nature. Finite, circumscribed, and weak though he is, he yet attempts to fathom the meaning of himself and likewise of all that is about him. He sees the moon, the sun, the myriads of stars in all the glistening splendor of their orderly array, and like the babe that reaches out and longs for the object appearing before his vision, so man through his mental eye, aided by the instruments of his own invention, wanders out into the vastness of space, ever observing, ever asking: What is the meaning of all this? Whence has it come? Though he stand face to face with the immutable laws of Nature and with Eternity itself, his questioning mind still seeks to overstep the boundaries of its finiteness and strives to comprehend the infinite.

Matter

Through our senses we perceive nature, — the material world and its extraordinary variety of manifestations: we feel, see, smell, taste, and hear it. Most of it is inert, and though we see that it undergoes change in part, it remains lifeless matter, the material of the universe. On the earth, however, we note the presence of material bodies which in their ceaseless chemical change manifest life and vitality, the " vital force " of the Greek philosophers, and these bodies are cognizant of the material world surrounding them. They live in it, absorb and change it into their own living bodies, and pass this property of their substance on to other entities, their descendants, which are more or less like themselves. The fundamental difference between the quick and the dead is that one is endowed with the quality of *irritability*, that is, the ability to undergo some slight internal change in response to equally small alterations in the environment; while the other is part of the lifeless world that only to a limited degree responds by chemical and physical change to external and internal agencies.

Inorganic Matter

The earth is composed of matter which science recognizes as *inorganic* and *organic*. The former is lifeless matter, much of which is in the crystal form, and hence it is sometimes referred to as the *Crystal Kingdom*. Organic matter, on the other hand, when alive manifests vitality, either in the form of single cells or in aggregates of cells, and thus is classified on the basis of its cell structure and mode of nourishment into the *Plant Kingdom* and the *Animal Kingdom*. In other words, the entities occurring in the inorganic world are in the crystalline form, or in fragmental or altered condition; while the bodies of living matter have their substance organized into a mechanism capable of response to external and internal agencies, and are hence called *organisms*.

Complexity of Matter. — Matter, whether of the earth or of the rest of the universe, is complex, divisible, resistant substance perceivable by our senses. It can be distorted, moved, broken, comminuted, or otherwise modified, but cannot be produced or destroyed. There are three states in which matter displays itself, the *solid*, the *liquid*, and the *gaseous*.

Matter commonly exists in more or less complex substances which can be broken up by chemical processes into at least eighty-four elements, without including the unstable and temporary forms involved in radioactive disintegration (*uranium* and *thorium*, see page 250). Each one of these elements is a kind of matter that cannot be separated into other kinds; they occur in the earth under ordinary conditions mostly as solids, more rarely as gases, and least often as liquids.

The elements which are of chief importance in forming the rock-shell of the earth have been mentioned on page 304. To them may be added hydrogen, carbon, and chlorine. In the envelope of water (the hydrosphere) the composition is: oxygen (85.8 per cent), hydrogen (10.7 per cent), chlorine (2.1 per cent), sodium (1.1 per cent), the remainder consisting of other elements in small quantities. In living substance, or the material of the biosphere (*bios* means life, therefore the sphere of plants and animals), there are always four elements present in large amounts, namely, carbon, hydrogen, oxygen, and nitrogen. Water in large proportion, usually 70 per cent or more, is essential to life, as are also certain inorganic salts, the most important of which are chloride of sodium and salts of phosphorus, calcium, magnesium, potassium, and iron.

The combination of these elements into a colloidal or jelly-like compound represents the chemical basis of living matter.

Nature of Inorganic Matter. — Inorganic matter is lifeless material in the simplest condition. In the crystalline form it begins in a nucleal molecule or particle; it enlarges by external addition or accretion alone, and there is hence no proper development, as the crystal is perfect, however minute; it ends in simply existing, and not in reproducing; and, being lifeless, it has no proper death or necessary dissolution. (Dana.) In other words, a crystal grows by the external addition of materials chemically the same, or of the same kind, as itself, arranged in layers, the body always retaining the same shape and constitution and never exhibiting internal circulation, motion, assimilation of food, internal growth, or reproduction of its own kind.

Organic Matter *

Organic matter in any form when alive is endowed with life, a condition that no one is able to explain completely. Active life, however, has been found to involve the following facts: The living organism *grows* at the expense of material different from itself, and this material is added within the body, while crystals grow by external accretion of substance. It is subject to continual chemical change, and yet has the power of retaining its integrity, of remaining more or less the same for prolonged periods. The physical basis of life invariably includes complex carbon compounds known as *proteids*.

A living creature is a more or less perfect *integrate* of organic corpuscles, that is, its parts are combined into a unit to make the individual, which has a *unified* behavior and gives effective response to external stimuli.

Manifestations of Organisms. — A living organism exhibits five inherent activities, — contractility, the power of movement, which is better developed in animals than in plants; irritability, the power of responding to stimulus in the wide sense, also more marked in animals; nutrition or utilization of food; respiration; and excretion, which is again greatest in animals — besides the periodic activities of growth and reproduction.

These manifestations of living matter are seen even in the simplest of plants and animals, where the individuals are microscopic in size and the unit is contained in a single cell (Fig. 312 *B*

* This section is largely taken, either verbatim or in modified form, from J. Arthur Thomson's *Outlines of Zoology*, 4th edition, 1906: 21–51.

and *C*). However, living matter is more commonly seen and comprehended when many cells live together and form the unit or individual, that is, in the plants and animals as usually understood (Fig. 312 *A*). All these forms are said to have a *body* con-

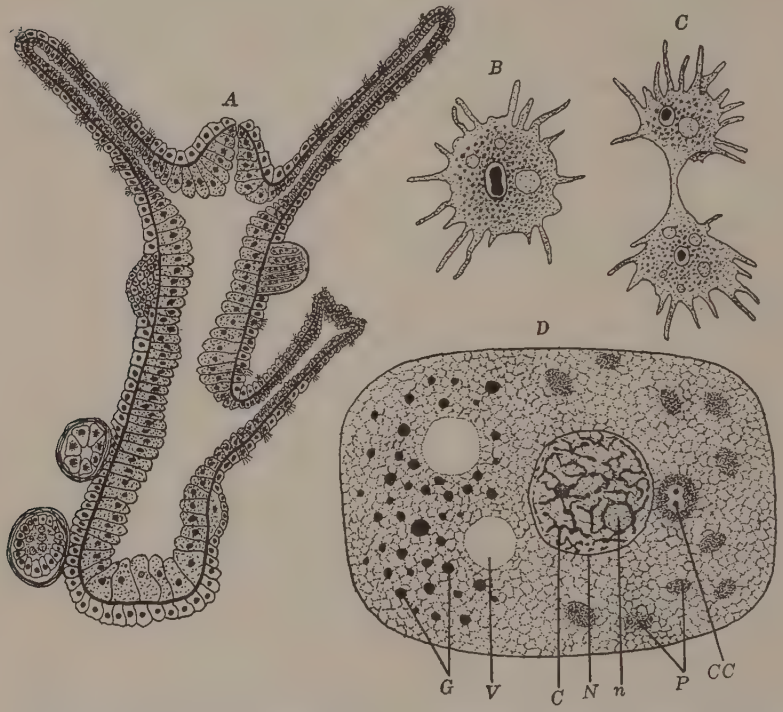


Fig. 312. — Cells and cell structure. *A*, a longitudinal section through the body and two tentacles of a fresh-water *Hydra*, to show the cell structure of a metazoan animal. Greatly magnified. *B*, a single-celled animal, *Amœba; C*, the same dividing into two individuals. Greatly magnified. *D*, diagram of cell structure. After Wilson. Very greatly magnified. *C*, chromosomes; *CC*, centrosome; *G*, granules; *N*, nucleus; *n*, nucleolus; *P*, plastids in the cytoplasm; *V*, vacuole.

sisting of unit masses or cells, which in the higher forms of plants run into countless numbers. It is impossible for these cells to remain the same, for as they increase in number they become diversely related to the outer world, to food, to one another, and so on. Division of labor, consequent on diversity of conditions, is thus established in the organism. In some cells one kind of activity predominates, in others a second, in still others a third, and this division of labor is associated with that complication of structure which is called *differentiation.*

Essential Differences between Plants and Animals. — The functions, cellular structure, and development in plants and animals are essentially alike, and there is no absolute distinction between them. These two groups are organisms differing in their totality of organization and in the detail of their functions; they have developed along two independent trunk lines since early in the earth's history.

When we contrast plants and animals it is easy to distinguish between such extremes as a fish and a flower, less easy to contrast a sponge and a mushroom, and well-nigh impossible to decide whether some very simple unicellular forms, which Haeckel called "Protists," have a predisposition toward plants or toward animals. We cannot do more than state average distinctions. The food which most plants absorb is cruder or chemically simpler than that which animals are able to utilize. Thus most plants derive the carbon they require from the carbon dioxide of the air, while only a few (green or chlorophyl-bearing) animals have this power; all the other plants and animals depend for their carbon supply on the sugar, starch, and fat already made by the green plants and animals. As regards nitrogen, most plants take this from nitrates and the like, absorbed along with water by the roots; whereas animals obtain their nitrogen from the complex proteids formed within other organisms. Most plants, therefore, feed at a lower chemical level than do animals, and it is characteristic of them that, in the reduction of carbon dioxide, and in the manufacture of starch and proteids, the kinetic energy of sunlight is transformed by the living matter into the potential chemical energy of complex foodstuffs. Animals, on the other hand, get their food ready-made; they take the pounds which plants have, as it were, accumulated in pence, and they spend them. For it is characteristic of animals that they convert the potential chemical energy of foodstuffs into the kinetic energy of locomotion and other activities. In short, the great distinction — an average one at best — is that most animals are more active than most plants.

Activity of Animals. — Most animals live an active life, in great part ruled by the two motives of love and hunger in their widest sense; they are busy finding food, avoiding enemies, wooing mates, making homes, and tending the young. These and other forms of activity depend upon internal changes within the body. Thus the movements of all but the very simplest animals are due to the activity of contractile parts known as muscles, which are controlled by nervous centers and by impulse-conducting fibers, and the energy involved in these movements, and in most other

vital activities, is supplied by the oxidation or combustion of the complex carbon compounds which form a substantial part of the various organs.

The work done means expenditure of energy, and is followed by exhaustion (muscular, nervous, etc.), so that the necessity for fresh supplies of energy is obvious. This recuperation is obtained through food, but before this can restore the exhausted parts to their normal state, or keep them from becoming, in any marked degree, exhausted, it must be rendered soluble, diffused throughout the body, and so chemically altered that it is readily incorporated into the animal's substance. In other words, it has to be digested. A fresh supply of oxygen and a removal of waste are also obviously essential to continued activity.

We may say, then, that there are *two master activities* in the animal body, those of muscular and those of nervous parts. To these the other internal activities are subsidiary conditions, turning food into blood and blood into tissues, and thus repairing the waste of matter and energy, keeping up the supply of oxygen, sifting out and removing waste products, and so on.

Growth and Reproduction. — Besides the more or less constantly recurrent activities or functions, there are the processes of growth and reproduction. When income exceeds expenditure in a young animal, growth goes on, and the inherited qualities of the organism are more and more perfectly developed. At the limit of growth, when the animal has reached *maturity*, it normally reproduces, that is to say, liberates either parts of itself or special germ-cells which give rise to new individuals.

Protoplasm. — Protoplasm is the genuinely living matter, or, as Huxley happily expressed it in 1870, it is "the physical basis of life." It cannot be clearly stated what protoplasm is. Professor E. B. Wilson in 1896 said: "The ultimate basis of living matter is not a single chemical substance, but a mixture of many substances that are self-propagating without loss of their specific character." Thomson states: "Protoplasm is a marvellous form of matter in motion, or a subtle kind of motion of which we can form only a very vague conception."

Cells. — All complex organisms are made up of organs and these are composed of tissues that are contractile, nervous, glandular, etc. In turn the tissues are made up of cells, so that all organisms have a *cellular structure* and a cellular origin (Fig. 312 *A–D*). The simplest organisms are unicellular and the entire life process goes on in such single cells, each a unit mass of living matter; as

such all plants and animals begin. In the great majority of organisms, however, the body is made up of hundreds upon hundreds of cells combined into tissues and organs.

A cell is a unit mass of living matter, usually with a nucleus. Most cells are too small to be distinguished except through lenses; many single-celled animals (Protozoa) are just visible to our unaided eyes. The largest animal cells are eggs distended with yolk.

Plant Cells and Animal Cells. — In a general way it may be said that the cells of plants have firm, more or less thick walls enclosing protoplasm, with granules (chloroplasts) of green coloring matter (chlorophyl). This stiffness of wall structure isolates the living substance, and consequently independence of action, that is, movement, in plants, as compared with that in animals, is diminished. By means of the green coloring matter, plants have the power of producing their own nutritive substances from certain constituents of the air and water and from the salts contained in the soil, and they are thus able to exist independently; while animals are dependent for their nourishment, and so for their very existence, on plants. Plants are therefore the primary magazines of food.

Origin of Life

What is Life? — Everyone knows, or thinks he knows, what life is; at least, we are all acquainted with its ordinary, obvious manifestations. It would, therefore, seem that it should not be difficult to find an exact definition. The quest has nevertheless baffled the most acute thinkers.

Life has not been demonstrated to be independent of matter; it is always associated with very complex carbon compounds, and is always derived with change from previous life. For twenty centuries philosophers held that life was being constantly and spontaneously generated (*spontaneous generation*) out of inorganic matter, or that it arose out of dead animals, or developed as worms in the intestines of animals. All of the stated cases of spontaneous generation, however, have been proved to arise in invisible organic germs floating in the air and falling into water or other environment necessary to growth and development. In the case of dead bodies giving rise to new and very different life, this is now seen to be due to insects depositing their eggs in the carcasses of animals, where they feed and develop into maggots and other larval forms. Intestinal worms arise in eggs swallowed by the host.

On the basis of established facts in Biology it can be said that we know nothing of a positive nature as to the origin of life. It is the greatest of the unsolved problems confronting man.

Schäfer gives his opinion thus in 1912:

"Looking at the evolution of living matter by the light which is shed upon it from the study of the evolution of matter in general, we are led to regard it as having been produced, not by a sudden alteration, whether exerted by natural or supernatural agency, but by a gradual process of change from material which was lifeless, through material on the borderland between inanimate and animate, to material which has all the characteristics to which we attach the term 'life.'"

On the other hand, it is now established that there is no sharp boundary between inorganic and organic chemistry, as organic compounds are produced from inorganic substances. Organic chemistry has become the chemistry of carbon compounds, but none of these compounds so far made evinces life, growth, or reproduction.

Ancient Origin of Life. — Life has been propagating life with change (evolution) probably ever since the earth has had a hydrosphere and atmosphere. How, where, and when it began is geologically unknown, and the only help the paleontologist can give is the proof that life has been on the earth countless ages. We note its presence indirectly for eon upon eon through its chemical action upon the elemental substances, as shown in the accumulation of carbonaceous deposits (black shales, graphite), limestones and dolomites, and iron ores, all of which in the earliest records of the earth are, however, without visible fossils. For the first time in the Proterozoic (Chapter XXIX) we meet with the actual remains of organisms, lime-secreting sea-weeds and annelids. This evidence seems not to be in accord with the theory derived from a study of living organisms, which demands that the earliest forms of life should be the most lowly kinds, for these fossils are highly organized. However, these occurrences in the ancient rocks do not disprove the theory that life began in simple microcosms, rather are they indirect evidence confirming the theory. The primordial life was in all probability exceedingly minute and too perishable to be preserved as fossils; it attained maturity, propagated, and vanished with astonishing rapidity. Slowly in the course of the eons the individual cells attained to larger growth and greater complexity; some congregated and lived attached to one another as a colony, but still kept their individual independence, and this neighborly association led to division of labor among the cells, to the formation of localized functions, and finally to the development of tissues

and organs. Thus was developed a "body," a greater and better organic workshop and a resistant mass wherein was also stored a greater amount of food, all of which finally led to longevity.

Classification of Organisms

Basis of Classification. — It is instinctive with humanity to group things of a kind together; for instance, animals that feed on plants we speak of as plant-feeders (herbivorous), those which seek flesh for food we know as flesh-feeders (carnivorous). However, a natural classification is not based on mere superficial resemblances, as is sometimes thought by people who are not naturalists, and who speak of all animals that inhabit the ocean as fishes, a fact which has led to the inclusion of the whales under this term, although they are truly warm-blooded mammals and nurse their young with milk like those living on the land. Systematic biologists, that is, students of organic relationship, are careful to select, as a basis for grouping, such characters as have a fundamental significance leading to the discovery of natural descent, organisms with the same structure and related genealogy being classed together. This means not only that the organisms so grouped must be structurally alike at maturity, but also that they must have a very similar life development from the egg onward. The study of the stages of growth in the individual is the science of *Ontogeny*, which includes *Embryology*. This study is also applicable to the fossils and we can thus trace more or less imperfectly the history of living things back into their geologic ancestry, and the process may be continued into the most remote times. Therefore the botanist and the zoölogist must coöperate with the paleontologist in the grouping of organisms into natural classifications. In addition, the paleontologist notes the appearance of the organisms in the stratified rocks, this time sequence being called *chronogenesis*. Therefore the named divisions in any scheme of organic classification are finally based on organic structure, ontogeny, phylogeny, and chronogenesis.

Grouping of Organisms. — All organisms are divided into the plant kingdom, or *Plantæ*, and the animal kingdom, or *Animalia*. These are the largest divisions, and while all organisms are referred to one or the other of them, in reality a sharp boundary line between plants and animals first becomes possible when they exhibit a complicated structure. This, however, is in accordance with the theory of evolution, which holds that the higher organisms have

been evolved from the lower. In common practice there is no difficulty in distinguishing plants from animals.

The kingdoms of plants and animals are each again divisible, like the parts of a tree, into other and smaller groups, of which there are many categories. In this place only the larger ones will be considered. After kingdoms come the great trunk lines, or stems, of organic structures, each one of which is known as a phylum (plural phyla), and so the grouping continues into smaller and smaller divisions until finally the individual is catalogued, the unit and basis of all classifications. For easy reference these various divisions may be grouped as in the following example:

Kingdom (Animalia);
Phylum (Chordata, or vertebrate animals);
Class (Mammalia, or mammals);
Order (Carnivora, or carnivorous animals);
Family (Felidæ, the cats);
Genus (*Felis*, a member of the cat family);
Species (*Felis tigris*, the tiger);
Individual.

Names of Organisms. — It is the ambition of naturalists to name all plants and animals, living and fossil, and according to the *rules of nomenclature* regulating this proceeding, each species, that is, a group of individuals which resemble one another in certain characters, is to have two names. The first one is called the generic name and is taken from the Greek or Latin language; for instance, the genus *Elephas* from the Greek *elephas*, elephant, and the genus *Felis* from the Latin *felis*, cat. A genus may contain but a single species or it may have several or even many, but in all cases where the species are grouped under the same generic name, it means that all have in common the structural characters on which the genus is founded. The specific name is taken from the Latin language or is a Latinized form of a word from another tongue; for instance, the common house cat is called *Felis domestica*, the lion is *Felis leo*, the African elephant is known as *Elephas africanus*, and the Indian form as *Elephas indicus*. This double naming is called *binomial nomenclature* and was established by Linnæus in the year 1735.

In America it is the custom to write the generic name with an initial capital letter and the specific and varietal names, of whatever significance, with an initial small letter. Both names are written in italics.

Divisions of the Plant Kingdom. — The plant kingdom may be divided into two subkingdoms, the *Cryptogams* and *Phanerogams*. The former, of which mushrooms and ferns may be cited as examples, include an extraordinary variety of the most different plant forms, extending from unicellular organisms to plants exhibiting division (segmentation) into stem, leaf, and root. Cryptogams propagate by unicellular spores, which they set free. They include three phyla (or stems) of which only the Pteridophyta (ferns, rushes, and club mosses) will be considered in this book. The Phanerogams have seeds, multicellular bodies in which is included the embryo of a plant. In other words, Cryptogams are "spore plants," while Phanerogams are "seed plants." The latter include the most highly developed forms, such as our common garden plants, and are also often called "flowering plants," because all of them have flowers, while the Cryptogams may or may not bear flowers.

Divisions of the Animal Kingdom. — The animal kingdom is divided into two subkingdoms, *Protozoa* and *Metazoa*. In the former the individual or unit animal consists of a single cell, that may lead a free life independent of its associates, or with them may combine into colonies. In the colonial form, however, each cell is a complete individual and there is as a rule no division of labor among the members of the colony. In the Metazoa, or higher animals, as they are usually called, while the cells are also grouped into tissues and organs, there is always a division of labor among them. In other words, the Protozoa are usually very simple microscopic animals, almost unknown except to scientists, while the Metazoa are multicellular animals, varying greatly in size and of different degrees of complexity, and are more or less known to everyone.

The subkingdom Metazoa is commonly divided into the Chordata or *vertebrates* and Invertebrata or *invertebrates*. The former are the backboned animals, or those with internal bony skeletons, such as the dogs, cattle, birds, fish, and the like; while the latter are the backboneless animals such as the insects, worms, shell fish, etc.

The phylum Chordata is divisible into the subphyla (1) *Hemichorda*, or worm-like animals with distinct gills, the rudiments of future lungs in the higher vertebrates. None of these interesting animals, are, however, known as fossils. The (2) *Urochorda* or *Tunicata* include the sea squirts and ascidians, and seem to lie on the border line between invertebrates and vertebrates; but these also are not known as fossils. The (3) *Cephalochorda* or *Acrania* include a very small number of living forms, which have been described as "a far-off prophecy of a fish"; none are known as fossils.

The true vertebrates, or the subphylum (4) *Craniata*, include the following classes: *Cyclostomata*, the archaic fishes such as the hags and lampreys; *Pisces* or common fishes; *Amphibia* or newts, salamanders, frogs, and toads; *Reptilia* or turtles, lizards, snakes, crocodiles, and dinosaurs; *Aves* or birds; and *Mammalia* or mammals, the highest animals, which suckle their young with milk.

CHAPTER XVIII

EVOLUTION, THE CONSTANT CHANGE OF LIVING THINGS

Multiplicity of Organic Beings

Number of Living Animals and Plants. — Man is a part of nature, and he has classed himself as the highest Primate, the foremost member of the first among the groups of animals. He lives in an environment of organisms, but of the extraordinary variety of this life he generally has but the slightest conception. It is said that Aristotle (384–322 B.C.) described about 500 different kinds of organisms in his *History of Animals*, and it is probable that he knew more forms than any other naturalist up to a few centuries ago. In 1758 Linnæus noted in his famous work, *Systema Naturæ*, 4236 species, and Pratt in 1911 estimated the described forms as numbering 522,400. Of this total, 284,000, Ashmead states, are insects, and Howard estimates that when all the insects are described the number will be nearer 3,500,000. All of these animals are distributed, according to Stiles, in upward of 120,000 genera, to which each year are added 1150. Of living plants, on the other hand, fully 200,000 kinds are described and it is thought that this total will easily rise to above 300,000.

Number of Fossil Forms. — Among the fossils the number of known forms is much smaller because of the great imperfection of the geologic record. The degree of incompleteness in our knowledge of the organic past can be brought out with striking effect by the statement that upward of 13,000 species of living butterflies have been described, while of fossil forms only 22 are known, and one half of these are from a single locality, Florissant, Colorado. In 1820 there were known 127 species of fossil plants and 2100 of fossil animals. An estimate brought up to date places the number at about 100,000 species, and when this sum is contrasted with that of living described forms, the ratio is as 1 to 5. This, however, is very far from the exact truth, for we are contrasting all of geologic time with the very short present. If, then, we wish to determine the number of kinds of animals that have lived in the geologic past, we must multiply the 522,000 described species of living forms by at least 200 geologic units, as so far deter-

mined for North America, each one of which is at least the equivalent of Recent time; and even then the figures are thought to be far below the actual number of species that have lived. Though it is true that life became progressively more varied with time, still the comparison made is only with the described species and not with the estimated number of kinds that probably are living at present. Therefore it seems safe to state that for every 100,000 kinds of fossil animals that lived we probably know only 1044. "The whole geological record is only the skimmings of the pot of life," says Huxley; it does give, however, a vivid glimpse of the extraordinary array of organisms which peopled the world of the past.

We must now ask ourselves the old, old questions: Have the various organisms always been the same, and whence have they come? Were they *created* as we know them by the special act of a supernatural agency, or were they *evolved*, that is, derived by a process of change, from pre-existing organisms?

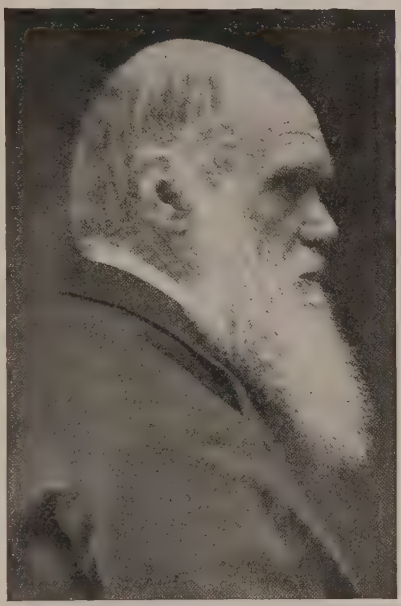


Fig. 313. — Charles Darwin (1809–1882). Father of the theory of evolution.

Theory of Organic Evolution

Rise of the Theory. — The ancient peoples had vague ideas in regard to this profound question, but it was not until the nineteenth century (1859) that Charles Darwin, by the application of true scientific methods, proved in his *Origin of Species* that life is evolved, with change, from previous life. His is the idea of *organic evolution* of species as opposed to supernatural creation.

"Poets, from Empedocles and Lucretius to Goethe and Tennyson, have sought in their verses to illustrate the beauty of evolutionary ideas; and philosophers, from Aristotle and Strabo to Kant and Herbert Spencer, have recognized the principle of evolution as harmonising with, and growing out of, the highest conceptions of science. Yet it was not till the Nineteenth Century that any serious attempts were made to establish the hypothesis of evolution as a definite theory, based on sound reasoning from careful observation."

The ancient tillers of the soil must have been impressed by the great annual miracle of the outburst of vegetable life as spring returns. " From the dead, bare ground they witnessed the upspringing of all the wondrous beauty of the plant-world, and, in their ignorance of the chemistry of vegetable life, they imagined that the herbs, shrubs and trees are all alike built up out of the materials contained in the soil from which they grow. The recognition of the fact that animals feed on plants, or on one another, led to the obvious conclusion that the *ultimate* materials of animal, as well as of vegetable structures, were to be sought for in the soil. And this view was confirmed by the fact that, when life ceases in plants or animals, all alike are reduced to ' dust ' and again become a part of the soil — returning ' earth to earth.' "

Among the eastern Mediterranean peoples arose the ideas that " the world " had a small number of plants and animals that were suddenly created supernaturally, and that from time to time they were destroyed. Thus were the doctrines of *creation* and *catastrophism* developed by these eastern nations, surrounded as they were by sudden floods, earthquakes, and volcanic outbursts (see page 5).

In Egypt, out of a very different environment, grew another doctrine. " Instead of sudden floods and terrible displays of volcanic and earthquake violence, they witnessed the annual gentle rise and overflowings of their grand river, with its beneficent heritage of new soil; and they soon learned to recognize that Egypt itself — so far as the delta was concerned — was ' the gift of the Nile.'

" From the contemplation of these phenomena, the Egyptian sages were gradually led to entertain the idea that all the features of the earth — as they knew it — might have been similarly produced through the slow and constant action of the causes now seen in operation around them. This idea was incorporated in a myth, which was suggested by the slow and gradual transformation of an egg into a perfect, growing organism. The birth of the world was pictured as an act of incubation, and male and female deities were invented to play the part of parents to the infant world. By Pythagoras, who resided for more than twenty years in Egypt, these ideas were introduced to the Greek philosophers, and from that time ' Catastrophism ' found a rival in the new doctrine which has been designated under the names of ' Continuity,' ' Uniformitarianism ' or ' Evolution.' " (Judd.)

Variability of Individuals and Species. — All observant and thinking persons know that a young horse is always a horse and never a zebra or an ass. In other words, animals during their growth do not change into other species, and even though they alter their appearance greatly from birth to maturity, these alterations are characteristic of the form observed and of no other. Therefore it is said that each species " breeds true " in its specific characters, and this relation between parent and offspring is called *heredity*. A close analysis of this resemblance, however, shows that it is never an exact one, for each individual of every species has its own peculiarities. No two organisms are exactly alike and these individual differences are grouped under the term *variation*. In other words, all organisms in their structural and physiological charac-

ters vary more or less in all directions, even though in general they closely resemble their parents.

The Struggle for Existence. — Organic nature in all of her wondrous beauty and astonishing variety appears to the careless observer to be in a condition of ease, play, and contentment. Play, however, generally means getting food, and contentment is at the expense of pain and death to another individual. Truly all organic nature is continually struggling to maintain itself, in the securing of food, in resisting unfavorable environmental conditions, in mating, and in the effort to rear its young. Death is inevitable in the *struggle for existence*, overtaking most of the organisms while they are still young, and hence few are maintained to maturity to propagate their own kind. The world is, nevertheless, and always has been fully populated, since each species unconsciously seeks at the very least to maintain its own numbers or to increase them. For this reason more young are born each year than can possibly exist. Some species produce but a single offspring, while others cast upon the world a million or more during the season of reproduction. Life's struggle is exceedingly harsh toward the young; they are mercilessly weeded out because of unfavorable habitations and starvation, snapped out of existence by a predaceous enemy, or made sick unto death by extremes of heat or cold, or by bacterial diseases. Success in life is the rare exception. In a struggle so severe any advantage, however slight, may therefore be decisive in prolonging the life of the individual and stimulating the origin of new variations. Nature constantly eliminates the unfit, and through the survival of the fittest, a process that Darwin called the law of *natural selection*, the species are maintained, though with constant alteration. The whole course of evolution, therefore,

Fig. 314. — Alfred Russel Wallace (1822–1913). With Darwin, the father of the theory of natural selection.

centers in the processes of reproduction. The favored individuals transmit their valuable qualities to their offspring, generation after generation. "The appearance of the desirable quality is an example of variation; the survival of those individuals which possess these qualities is secured by natural selection; and the perpetuation of the useful qualities is secured by heredity" (Metcalf).

Theory of Use and Disuse. — Jean Baptiste de Lamarck, during the years 1801 to 1815, was the first to elaborate a theory of organic evolution. To him, "Time and favorable conditions are the two principal means which Nature has employed in giving existence to all her productions." Under the diverse influences of the environment "the faculties increase and become stronger by use, become differentiated by the new habits preserved for long ages, . . . and are propagated by generation." In other words, organisms change because of the variability of the environment and through the use and disuse of their organs. This is the theory of *mechanical genesis* so firmly believed in by many American paleontologists.

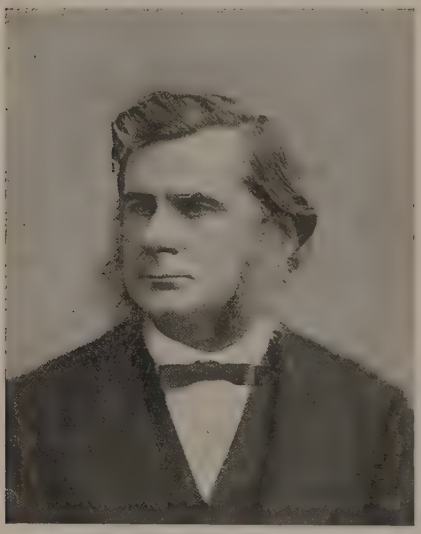


Fig. 315. — Thomas Henry Huxley (1825–1895). The great defender of evolution and exponent of the natural sciences.

Influence of Environment on Organisms. — So long as the environment of organisms remains unchanged, they undergo comparatively little modification, and such conditions prevailed during long geologic times. However, as the earth's shell has been periodically raised into mountain ranges and the oceans have as often flowed widely over the continents, it follows that the environment of plants and animals has undergone repeated and vast alterations. When the seas flowed over the continents, the habitable areas, or *habitats*, of marine life were enlarged at the expense of the land floras and faunas. The struggle for existence among the land plants and animals was therefore made harder, and evolution was quicker among them. Contrariwise, when the seas contracted, the struggle among the marine forms was enhanced,

due to diminished space, and on the lands the former mild climates were apt to change into more or less arid ones. Not only this, but many times mountains were thrown up simultaneously in many lands, thus bringing on great reductions of temperature and even glacial climates. Such changes led to the "critical periods" in the history of the earth, times especially fraught with danger to the organic world, and affecting deeply not only the life of the land but equally the shallow-water marine forms. Evolution was then especially rapid, blotting out floras and faunas that had long dominated the earth, and forcing the rise of new races which in their turn quickly attained mastery over their physical and organic environment.

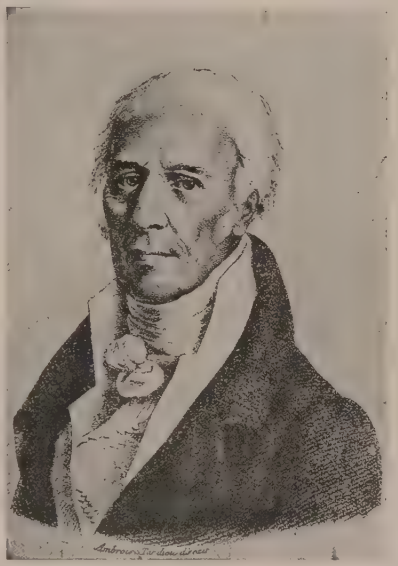


Fig. 316. — Jean Baptiste de Lamarck (1744–1829). Father of the theory of mechanical genesis in evolution.

Striking Examples of Adaptation to Environment. — "Of the several environments to which vertebrates have become adapted, the two which most profoundly modify their inhabitants are the water and the air. This is in part due to the fact that a homogeneous environment pressing upon all sides of the organism with almost the same intensity has moulded the form into a symmetrical contour which offers but little resistance in passing through the medium. . . . .

"Aquatic life modifies its denizens the more profoundly, because it becomes permanently sustaining, while even the best of fliers must ultimately return to the trees, the earth, or the sea. The aërial forms therefore always retain functional structures to enable them to move in the environment whence their ancestors came. Of the more perfectly adapted aquatic types this is not true. . . . .

"Altogether no fewer than seventeen separate evolutions for aërial life have occurred among vertebrates, true flight five and probably seven times, and soaring at least ten times." Four different stocks of fishes have learned to move in the air by flapping their pectoral fins; one frog soars; three stocks of Reptilia either soar, flap, or sail; all of the birds flap or sail; while amongst the mammals seven soar, and one, the bat, flaps its wings. (Lull.)

Among the invertebrates the insects have learned to fly remarkably well and even some spiders can float away in the air attached to long silken strands of their own making.

Of land animals, many stocks have gone more or less permanently to sea. This adaptation is rare among the spiders and insects, common among the reptiles

of the Mesozoic, less common among the birds, and has occurred several times among the mammals (porpoises, whales, and seals). In some of these animals the body transformation has been very great, not only by modification of the limbs, but even by the complete loss of them in some cases.

Finally, the eel-shaped type of body, one of the easiest to propel through the water, has been developed in this medium at least forty-four times, it being a common adaptation among the fishes, amphibians, and reptilians, including the snakes.

Definition of Species. — Lamarck correctly held that species are not fixed entities, and further that there are no sharp divisions in the organic world corresponding to the classes, orders, and genera of our biologic classifications. "A species," he wrote, "is a collection of similar individuals which are perpetuated by generation in the same condition, as long as their environment has not changed sufficiently to bring about variation in their habits, their character, and their form."

Evidence Proving the Theory of Organic Evolution

That all of the manifestations and complexity in the organic world have come about through descent with modification is shown in the following facts: (1) The living organisms are not distributed at random throughout space, but exist where we find them because of prehistoric conditions (Geographic Distribution). (2) All organisms are related to one another and this determined relationship can be readily visualized in a genealogical tree wherein the degree of ancestral parentage is shown in the trunk, main branches, stems, and leaves (Classification). (3) In related adults the organization and structures are alike, and these are unlike in unrelated stocks (Morphology). (4) The lines of descent are in a measure repeated during the earliest stages of growth in the individuals (Embryology). (5) The appearance of plants and animals throughout the geologic past is in harmony with the theory of progressive evolution from the structurally simple to the more complex (Geology and Paleontology). These topics will now be discussed in detail.

Geographic Distribution. — According to Gadow, "The subject of geographical distribution is the dispersal of life in space and time. The key to the present lies in the past." A little insight into the living organisms soon reveals the fact that the kinds of plants and animals are not of universal distribution. Every one knows that elephants and lions are found only in Africa and Asia,

and the giraffe only in Africa, that reindeer and caribou are restricted to northern lands, kangaroos to Australia, and humming birds to North and South America. While this restriction is largely controlled by temperature, yet that is not the whole cause, for we know that the tiger of southern Asia lives also in Siberia, where it has fortified itself against the cold by the growth of a thick fur. Restriction of species is further controlled by mountain ranges, moist and dry climates, forest and open plains regions, and chiefly through isolation of the land masses by the oceans. These are the *barriers* of the biologist, which prevent free intermigration between areas. Another kind of barrier which confronts animals in their wanderings is exposure to the local diseases caused by parasitic organisms. However, these barriers do not explain, for instance, the present wide distribution of the bears in Europe, Asia and America, where they range from the cold north into tropical Brazil, and from Siberia into Alaska, lands that are now separated by at least a hundred miles of ocean surface. But when we are told that in the geologic past Asia and America were united by a land connection, a *land bridge*, and that both had a warmer climate than at present, it is readily seen that the bears could have spread from the former continent into North America and so finally into South America. In other words, the present geographic distribution of organisms is not wholly due to the environment of to-day, but is further conditioned by that of the geologic past (paleogeographic distribution).

Also, similar environments do not produce identical organisms. Life descends from life, and as it is slowly but constantly changing in response to the constant alteration of its environment, the forms change and under favorable conditions the individuals grow ever more numerous and spread in wider and wider waves of wanderings, though, on the other hand, some organisms continually succumb under the struggle for existence. Species originate locally, and though some may remain thus restricted, others spread from their *dispersal centers* into wider areas according to the favoring nature of their surroundings and geography. These conditions are the controlling factors underlying the dispersion of all life, whether of the land or of the waters.

Classification. — The very fact that there are individuals of a kind that can be grouped into species and these into genera establishes the view of relationship. The further fact that in many cases there are no distinct differences separating the species or even the genera is further proof of descent with change.

Morphology (from the Greek word *form*, hence the science of form). — "According to the evolution theory, all higher organisms have descended from the lower by a process of transmutation. . . . This bond of union is first and foremost expressed in the morphological traits of the related species. For as the related animals (or plants) are descended from the same ancestral type, they must possess on the whole the same anatomical structure and organization, more or less modified in each individual case according to the life-habits of the organism. It is this fundamental identity of structure that we mean when we speak of the 'unity of type' in a given class of organisms, while the different parts and organs which are built on the same general plan in the various species are said to be homologous. In contradistinction, analogous organs are such as fulfil the same physiological function without possessing the same anatomical structure, as, *e.g.*, the wing of a butterfly and that of a bird, which, though both serving for flight, are constructed each in a totally different manner." (Herbert.)

Homologous structures offer the most striking evidence for the transformation of species. A good example is seen in the limbs of vertebrates, where the main muscles and bones are alike in a frog, reptile, horse, dog, or man. In detail, however, there are marked variations; in man, for instance, there are five fingers and toes, while the horse has only the third finger and toe remaining, although if we trace the ancestry of the modern horse into the geologic past we learn of fossil horses with three or four functional digits on each limb and with the rudiments of the remaining ones still present to show that the ancestral forms had the primitive five digits in use on each limb.

In the animals just mentioned we pass from homologous structures to *vestigial structures*, for the one-toed living horse still has in each limb the vestiges of the second and fourth digits, known as the splint bones. The same is true in the fossil horses, but in the oldest ones the splint bones are the vestiges of the first and fifth digits. The whales and porpoises of the oceans are descended from land mammals which had four legs adapted for walking, but the front limbs of these ancestors have been greatly modified in the living forms into swimming paddles, while the hind ones are to all outward appearance gone, although in reality the vestiges of them lie buried deeply in the flesh. In most of the snakes not even traces of any of the limbs are present, but in the python or boa there remain bony vestiges of the hind limbs. In the birds, similar loss of the front limbs can be observed, as, for instance, in

the flightless ostrich, whose wings are not fully developed, while in *Hesperornis* of the Cretaceous (Chapter LI) there are no wings, but deep in the flesh lies a single bone, representing the former wing.

Through disuse once useful organs may be largely lost, never to be recovered by subsequent descendants. In many animals the use of remaining relics is not always easily discerned, for these *vestigial structures* are but traces of former important organs. In man there are 180 such vestigial organs which serve no useful purpose, and which prove his animal descent. The human embryo in its earliest growth has a distinct external tail, and in every adult there is the vestigial vermiform appendix, "a small blind process leading from the large intestine, which, serving an appropriate function in vegetable-feeding animals, survived as a useless structure in man, and is at times even a source of danger." (Herbert.)

Embryology. — Embryology is the science which relates to the development of embryos, or the earliest stages of individual growth before the assumption of the distinctive form and structure of the parent. All living things begin their existence in a single cell that may be compared to the unicellular plants and animals, the most primitive condition of organisms; the original or mother-cell in the higher multicellular entities giving rise by repeated divisions to the adult specific organism. In this way each multicellular plant and animal recapitulates in a condensed and foreshortened way its ancestral history. This law was first formulated by the great German biologist, Haeckel, who termed it the *biogenetic law* and defined it thus: "The Ontogeny (development of the individual) is a short recapitulation of the Phylogeny (development of the race)."

In the highest vertebrates, including man, the embryos during their development pass through a series of transformations which represent roughly the evolutionary stages of their lower vertebrate ancestry. In the earliest of these stages there is hardly any difference between the embryo of a fish, salamander, tortoise, chick, hog, calf, rabbit, or man. This can only be explained on the supposition that all of these animals had fish-like ancestors. In the succeeding stages among the mammals, the embryos repeat practically only mammalian characters, thus showing that the ancestral history between the fishes and mammals has been eliminated or crowded out of their embryonic development.

Geology and Paleontology. — A great array of fossils is now known, and their appearance in geological time (chronogenesis) has been determined. Geology begins in darkness, with an ab-

sence of all fossils, but this very want of organic record is evidence that the earliest forms of life were perishable and could not have had the complexity of later organisms. In younger strata, however, there is an abundance of fossils, but nevertheless for a long time there is no evidence of land plants, and a land flora does not appear until still later times.

Not an insect is known until long after the appearance of the land floras. The earliest forms so far found were large plant-eaters and carnivores, but unlike the modern forms. They were followed by the most primitive of modern insects, the may-flies, dragon-flies, and true cockroaches; later appeared still higher types, but the dominant modern forms did not come until the rise of the flowering plants on which they were dependent.

Among animals, the first to appear were all water-breathers, and out of them arose the air-breathers. Not a shred of evidence for the existence of animals with backbones (vertebrates) is at hand until long after the backboneless forms (invertebrates) originated, the first representatives of the higher type being the fishes. Later came the higher amphibia or salamander-like animals, and out of them were developed the primitive reptiles. Reptilian birds with teeth appeared after the reptiles, and these but recently, geologically speaking, gave rise to the modern toothless birds. On the other hand, reptilian mammals originated earlier than the birds, and through a long process of evolution finally gave rise to the placental mammals, the highest type of animals. Finally, the line of mammals leading to man appeared first in the lemurs (monkey-like animals), shortly afterward came the true monkeys, and more recently arose the anthropoid apes and the ape-man.

Such evidence must convince anyone of the fact that the organic world proceeded to develop in an orderly sequence from the simpler to the more complex types of structures and from the lower to the higher mentality. The higher intelligence had its origin, not in the sea but on the land, where the most severe of environments placed a premium on the ability to meet and master new conditions. It was long in the making and not until geologically recent times did mind begin to evolve with wonderful rapidity in most of the mammals, and especially those in the line of man's ancestry. Contrast the intellectuality of the dinosaurs, rulers of the medieval world, with a brain weighing one pound in a body of thirty-eight tons bulk, and man, master of the modern world, with a brain ratio of four pounds to one hundred and fifty of flesh and bone!

The Truth of Organic Evolution. — The question is often asked by those unfamiliar with the work of biologists: Is the theory of organic evolution widely accepted by the students of organisms? The answer is that scarcely any worker in the sciences of Botany, Zoölogy, or Paleontology now rejects the theory; in fact, all work in these studies is based on the concept of life having continuously descended from life with change since it began on the earth. There is now no question about the truth of organic evolution as opposed to the theory of special creation. What is under discussion among the biologists is the method by which nature has brought about the manifold organic changes that we see. No more intricate problem confronts man. It is therefore not remarkable that the entire solution or even the main parts of it are not yet at hand. The secret is buried in each individual and he cannot reveal it, but the time will come when the *modus operandi* of it all will be proved by the biologists. The old notion of eternal unchangeableness with occasional upheavals has given way to the newer idea of progressive development, not only in organic nature but in all matter in space and time. Of Charles Darwin, who first placed this doctrine on a firm scientific foundation, it has recently been said: "In all the glorious company of immortal dead whose earthly frames are gathered in England's great mausoleum, there is no other one who has done so much to modify the mind of thinking man" (Schmucker).

CHAPTER XIX

FOSSILS, THE GEOLOGIST'S TIME MARKERS

Living plants and animals constitute the present organic world, while fossils are the remains of organisms that have lived in the geologic past. Fossils may occur in any sedimentary rock of the low land near the sea, far inland, or even in the highest mountain ranges. They indicate not only the kinds of animals which have lived, but a great deal about the nature of their home surroundings as well. For example: the remains of a marine animal, such as a shark, now found naturally entombed in strata anywhere on the present land indicate that where the relic now occurs the sea existed at the time when the organism was living.

Ancient Views about Fossils. — The fact that fossils resembling in every way the shells of marine animals are now found far inland has long perplexed mankind. Some of the Greeks in the third and fourth centuries before Christ explained them as ineffectual attempts at creation by a *plastic force* inherent in the earth. This poetic interpretation arose again and again in the subsequent centuries, and the "controversy about fossils" was particularly acute after the fifteenth century. These occurrences were then regarded by many as mere mineral concretions and described as *lusus naturæ*, freaks of nature, while others said that these "figured" or "formed" stones were made in the soil of the earth under the influence of the stars. Still others correctly held that fossils could only have belonged to once living plants and animals, but attributed their presence in the rocks to the Deluge, believing that not more than 6000 years had elapsed since the time of the Creation and that the Flood had been universal, destroying all life and spreading its remains far and wide over the lands. "They had no conception of the physical impossibility of accumulating all the fossiliferous formations of the earth's crust within the space of one hundred and fifty days during which 'the waters prevailed upon the earth, and all the high hills that were under the whole heaven were covered,'" as Sir Archibald Geikie has said. Thus arose the "diluvial theory" and with it a bitter controversy that only ceased late in the nineteenth century.

In the Mediterranean countries, however, the younger geological formations " underlie many of the plains and rise high along the flanks of the hills. In these deposits, shells and other remains of sea-creatures have been preserved in such vast numbers as could not fail to arrest attention even in the infancy of mankind. Since the organisms are obviously like those still living in the neighboring sea, the inference could readily be drawn that the sea had once covered the tracts of land where these remains had been left. This conclusion was reached by some of the earliest Greek philosophers [especially Xenophanes, 576–480 B.C.], and there can be little doubt that it led to those wide views of the vicissitudes of Nature which were adopted in later centuries by their successors." (Geikie.) Thus arose the theory of " cataclysms and re-creations," one that was laid aside only in the past century for the theory of evolution, which teaches that life, once originated, has continued uninterrupted to the present.

Transition of Present Life into Fossil Forms. — The easy transition between the living marine molluscs (shell-fish) and their geologic ancestors is best understood by the following examples. The Pleistocene formation is the youngest of geologic deposits and in it, at a given locality, all of the species may be of still living forms, while at another place where the deposits are older, as many as 25 per cent may be of extinct species. In the still older Pliocene, less than half of the forms are of living kinds, and in the next lower formation, the Miocene, only from 20 to 40 per cent are of recent species. Finally, in the oldest of Tertiary formations, the Eocene, there are rarely more than 5 per cent of living shelled animals found.

What Fossils are, and What They Teach

Fossils have two values: (1) as " medals of creation," showing the course evolution has taken; and (2) as indicators of geologic time or chronology. As the first-mentioned value is of most importance in pure Paleontology and general Biology, it need not be treated in detail in this book. The chronogenetic value of fossils is, however, of great import in Historical Geology and needs, therefore, to be studied with some care. All life has constantly changed, not only as to specific form but as a rule in definite directions from the simpler to the more complex types of structures, although often also in the reverse manner. For these reasons, fossils are of the greatest value in determining the past history of the earth.

Evolution and Superposition. — To ascertain the course evolution has taken the fossils must also be studied in the order of their

appearance in any given series of rocks, and this is done by noting their occurrence in the strata. Those in the lower rocks naturally must be older than those in the higher or superposed strata. The order of superposition is usually determined in regions where the earth's crust has not been disturbed, for here bed upon bed of rock occurs as laid down by the waters (see Fig. 205); but where the strata are faulted or deformed into mountains the natural order of stratigraphic sequence is at times very difficult to ascertain. However, after one hundred years of endeavor a great deal of knowledge has been worked out as to the evolutionary sequence of organisms, and this knowledge, as determined in many countries, can now be relied upon to fix in turn the stratigraphic sequence.

Definition of Fossils. — This topic has been briefly mentioned on page 268, but may now be more fully treated. Fossils or petrifactions are the remains or natural impressions or even traces of plants and animals which have lived at some time previous to the present and are now buried in stratified rocks. The degree of perfection may vary all the way from the rare occurrence of an entire elephant preserving not only the skeleton but all the soft parts as well, to the imprint of a leaf in shale or sandstone. Fossils, however, are nearly always only parts of once living things, and it naturally follows that such specimens must have very different values in Historical Geology and Biology. Then these organic traces, though usually of extinct species, may also be of still living forms. In other words, the present life shades gradually into that of the geologic past, this transition being most gentle among the marine invertebrates, while but few of the living species of land-inhabiting vertebrates are known in the geologic formations. This is because evolution has gone on more slowly among the marine invertebrates and the land plants, and most rapidly among the land mammals. Moreover, the accident of burial has much to do with these decided differences between the kinds of organic records, for an animal living in the shallow sea and especially in or on the sea-floor is in the most favorable place for entombment, while only those animals of the land can leave fossils which live in, or whose bodies are swept into, some area where sediment is accumulating; the most abundant land fossils being remains of those animals which dwell on delta plains or partly within the rivers.

Preservation of Organisms. — Fossils always occur in sedimentary or stratified rocks that have been laid down in bodies of water, or on the lands through the action of the winds. Another

type of sedimentary strata having the possibility of fossils consists of volcanic ashes, which at times of outburst are shot high into the atmosphere and then carried by the winds for shorter or longer distances over the lands or seas, burying all living things. In this way the Roman summer resort, Pompeii, was buried by ashes

Fig. 317. — A tangle of fossil moss-animals (Bryozoa). Originally carbonate of lime, now replaced by silica, and etched out of limestone. A true pseudomorph without the microstructure.

from the volcano Vesuvius in the year 79 A.D. To-day in digging out the city some of the victims are found in the form of molds, so that when these hollow spaces in the fine ashes are filled with plaster of paris, good casts of the people and animals as they appeared in the flesh are obtained; such may be seen in the National Museum at Naples. The bones of human victims are also occasionally found under a thin flow of lava, as is the case at Pedregal de San Angel, near Mexico City. However, fossils are not often found under or in the basal sheet of lavas and it may therefore be said that in general they do not occur in igneous rocks. On the other hand, strata that have been replete with fossils may lose every recognizable trace of them by being subjected to the heat of large igneous intrusions, or more commonly by suffering great pressures during times of crustal deformation resulting in ranges of mountains, as described in Chapter XIII. These are the metamorphosed rocks, and whether recognizable fossils are present in them or not depends upon the character of

the sediment of which they are composed and the degree of alteration which they have undergone.

Any dead organism exposed to a temperature above the freezing point of water is, as a rule, at once attacked by bacteria and scavenging animals, and soon vanishes without leaving a trace of its former existence. In this process the oxygen of the atmosphere also assists, and the same is true for organisms under water, only in the latter case complete destruction is slower. The dissolving effects of circulating waters in most cases complete the destruction of even the harder skeletal parts. In other words, the individuals of entire floras and faunas are seen at the present time to vanish

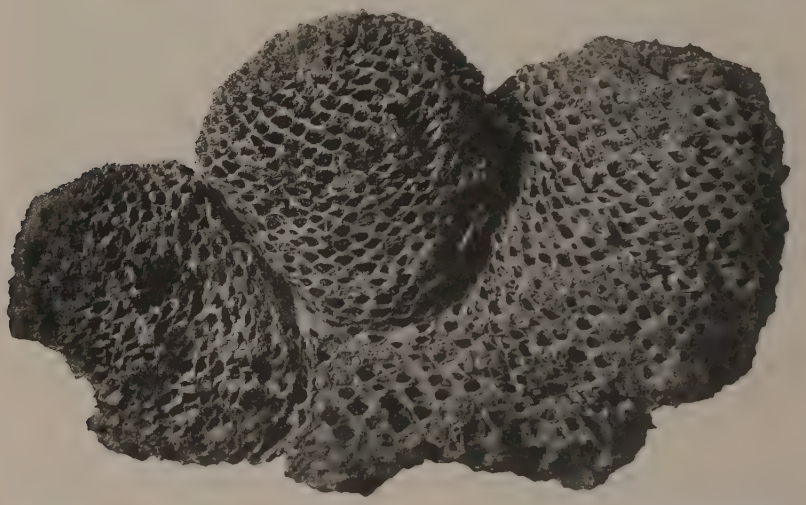


Fig. 318. — A fossil cycad, or plant distantly related to palms. The original wood is replaced by silica, yet the microstructure is preserved. See Fig. 319.

under the influence of other living things, and of the atmosphere and hydrosphere. It is probable that more than 99 per cent of all life has thus been removed. Every organic trace may be oxidized and dissolved into the elements from which it came — into the air, water, and the dust of the earth. Therefore, if an organism is to be preserved as a fossil it must be covered quickly by sediment, and even then only a mold of the exterior form may remain. Complete destruction is the rule among all organisms having soft bodies devoid of hard skeletal parts, and it is the exception among such to leave behind even a mold of their bodily form. Where there is a skeleton, either external, as shells, or internal, as the bones of vertebrates, it again depends upon the

chemical nature of these structures, upon the character of the sediment, and finally upon the chemical content of the waters in the rocks whether these parts are to be preserved or only to give evidence of their existence in the condition of molds.

Nature of Preservable Parts in Organisms. — The skeletons of plants are very rarely made of *silica*, this condition being found only among the single-celled and microscopic diatoms (see Fig. 329). Among the animals, silica is also used sparingly, and is almost wholly restricted to those forms living in the sea. The microscopic diatoms and radiolarians (see Fig. 330) use it freely and among the sponges probably somewhat less than one half have a

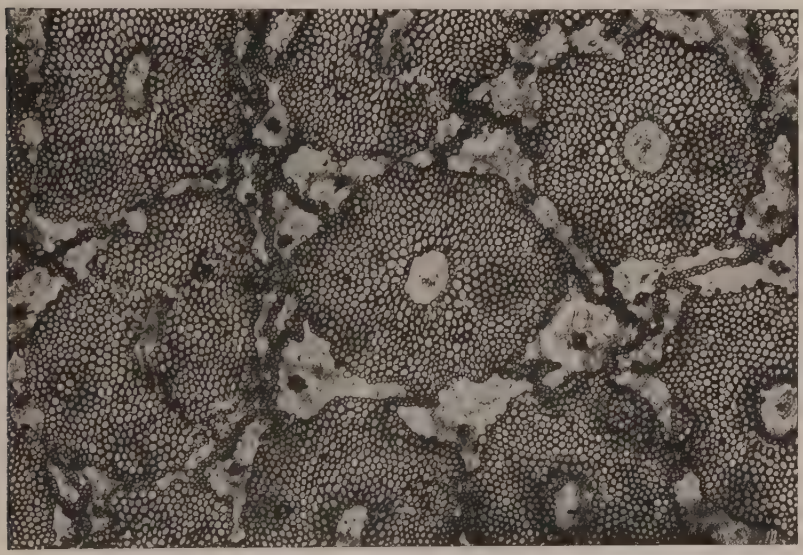


Fig. 319. — The microstructure of a fossil cycad. See Fig. 318.

siliceous skeleton. In these sponges the silica of the skeleton is in the colloidal form (not crystalline but like opal) and is therefore easily destroyed during the process of organic decay; hence the Silicispongiæ (see Fig. 381) are rarely preserved as fossils and are common only in Mesozoic strata. Among the diatoms and radiolarians, however, the silica occurs in the insoluble form and is very rarely destroyed at the time of deposition or afterwards.

Calcium carbonate is used liberally by many types of invertebrates but in plants it is utilized freely only among the marine and fresh-water calcareous sea-weeds. Here the sulphate of lime of the waters is converted by the organisms into the carbonate of

lime of their skeletal structures, bound together by an organic basis. This secretion is known as *conchin* and crystallizes in two mineral forms known as *aragonite* (prismatic in crystal form and cleavage) and *calcite* (cleavage more highly perfect and in three directions equally inclined to each other. See Appendix A). Sometimes a structure consists entirely of aragonite or entirely of calcite, but usually both forms exist in the same individual, as for instance among the Mollusca, where the inner mother-of-pearl layers are of aragonite and the outer porcelanous layers are of calcite. In other cases the calcite predominates, as in the oysters. At times the granules or fibers of mineral matter in the shells are associations of aragonite and calcite. It is very important to know this, because structures in the form of calcite, or in which this mineral dominates, are very apt to be preserved as secreted by the organisms, whereas such parts, when secreted as aragonite, are very rapidly dissolved away during decomposition or are replaced by other minerals through the agency of the percolating waters in the rocks. In the Paleozoic rocks it is almost the rule for the aragonite structures to be gone, this being especially true among the Mollusca, but in the Mesozoic and Cenozoic the mother-of-pearl layers are much more commonly preserved. Just why this is so is not yet determined. The internal skeletons of vertebrates, the bones, are composed largely of phosphate of lime bound together by an organic compound (collagen).

Other much thinner, and usually somewhat flexible skeletal structures consist of a compound of the nitrogenous substances of the ammonia group and a carbohydrate, known as *chitin*. This material has great resistance to chemical agents and is therefore hard to destroy. Among fossils it is often preserved in one form or another. Chitin makes the external skeleton of many kinds of invertebrates, for example, the arthropods (crustaceans, trilobites, insects), and to it is often added lime salts. A similar substance is *spongin*, which composes the fibers in bath sponges; this is rarely preserved among the fossil forms. *Keratin* contains sulphur in addition to nitrogen, and is but very rarely preserved among the fossils; it makes up the hairs, nails and horns of mammals, the feathers of birds, and the scales of fishes.

Preservation of Soft Parts. — It has been stated above that the soft parts of animals are only exceptionally preserved, and it is desirable to mention here a few of the examples of such preservation. Muscles are composed of fibrous material which sometimes is quite tough. If not destroyed by bacterial action, the muscle fibers may be preserved, flattened into thin layers, and in this way

they are often found associated with the skeletons of fishes, even as early as the Devonian, and of reptiles, particularly the Ichthyosaurs (Chapter XLVII) of the European Jurassic. Among the land vertebrates living under dry climates, the muscles and tissues may dry up over the skeleton and be preserved. Notable examples are the Egyptian mummies (none of which, however, are thought to be older than 10,000 years), large parts of the skin of great sloths in the caves of Argentina, and, among the Cretaceous reptiles, at least one large and extraordinary dinosaur mummy (*Trachodon annectens*), which may be seen in the American Museum of Natural History, New York City.

Sir Charles Lyell states that human beings have been buried in the peat bogs of England and Ireland and are preserved intact for hundreds of years due to the antiseptic properties of these marsh waters.

Grave diggers often relate the finding of "petrified human bodies." Such cases relate to fleshy people buried in very wet graves, in which case the entire body or parts of it may be transformed into *adipocere*, a waxy substance of a light brown color. During the slow decomposition of such bodies the organic matter is converted chiefly into an ammonium margarate with an admixture of the margarates of potassium and calcium; it is material that will soon vanish.

The most remarkable preservation of entire animals, however, is the case of those buried in the tundras (frozen ground, mainly ice) of northern Siberia, where great woolly elephants (*Elephas primigenius*) have been kept intact in natural cold storage. How long these carcasses have been entombed in the tundras it is difficult to say, certainly thousands of years, and yet the flesh when exposed on the melting of the ice is greedily devoured by the dogs of the Siberian peoples. The skeleton of one of these mammoths, found at the mouth of the Lena River, and another from Beresovka, with the mounted skin and skeleton and all of the internal organs kept in alcohol, are shown in the Royal Natural History Museum, Petrograd, Russia. A hairy rhinoceros (*Rhinoceros tichorhinus*) has been found in Siberia preserved in the same way, and similar but far less perfect preserval occurs in the frozen grounds of northwestern Alaska. Finally, large parts of the skin of a rhinoceros have been found well preserved in the petroleum seepages of Austria-Hungary.

Molds of the entire exterior of organisms are often found, even of such extraordinarily soft-bodied animals as the jelly-fishes or medusæ, in which the organic substance is at least 95 per cent water. The most wonderful examples of such come from the Jurassic limestones of Solenhofen, Germany.

Color Preservation. — It is exceedingly rare to find among the fossils a trace of their former color. When they are preserved in light-colored shaly limestones, the former color pattern may be present in dark bands, such being known as far back as the Ordovician. The mother-of-pearl color, or nacre, is, however, often preserved and especially well in limy shales impregnated with petroleum, but this color is due to the play of light in the prismatic or aragonitic portions of the shells, and not to a pigment in the material.

How Fossils Occur. — Fossils occur in any one of seven different natural conditions, three of which relate to the substance left by the organisms, three to their form, and one to both. (1) The great majority of fossil specimens preserve more or less of the original hard or mineral substance of the individual plant or

animal, and to this may have been added in the organic interstices more or less of other mineral substance during the process of fossilization, forming the *permineralized fossils*. (2) When the original mineral matter is exchanged for another and usually a dissimilar mineral, with the substitute preserving the original microscopic structure of the organism, the process of substitution is called *histometabasis* (two Greek words that mean *tissue exchange*) (Fig. 319). In this condition the woody parts of plants are often preserved and for study purposes are as good as the similar parts of living plants. (3) Plants may be completely *carbonized*, with the original organic structure more or less completely destroyed during the process. Such fossils have little paleontologic importance, but are of great economic value and are often used as datum planes in Stratigraphy

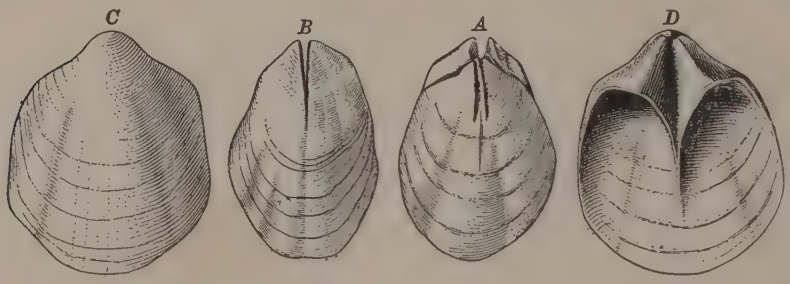


Fig. 320. — Four views of a brachiopod, to illustrate molds and casts. *A*, a natural mold of the interior of the joined shells as seen from the dorsal side. *B*, the same as seen from the ventral side. *C*, an artificial cast of the ventral exterior taken from a mold not illustrated. *D*, an artificial cast of the ventral interior taken from *B*.

and Structural Geology. The form of organisms with the original substance absent may occur in the rocks as (4) *molds*, (5) *imprints*, and (6) *natural casts* (Fig. 320). There is no marked difference between molds and imprints other than that the latter term is applied to impressions of thin substances, as leaves, etc. Natural casts are the counterparts of organisms made by nature by filling the molds of fossils with an uncrystallized substitute; (7) when the replacing material is a crystallized mineral, as calcite, pyrite, and more commonly silica in the form of chalcedony, the replacement is called a *pseudomorph* (from two Greek words that mean *false form*) (Fig. 317, also study Fig. 321).

Tracks of animals crawling around on the muddy floors beneath bodies of water, and especially in the sea, are very commonly preserved. Land animals also often leave their tracks in the geologic

record, but these, when of vertebrates, in most cases occur in red clays or sands laid down in deserts or at least in arid regions. Reptile tracks are often seen in the Carboniferous (Mauch Chunk) and are especially abundant in the Triassic.

Geologic Change in Organisms. — In Tertiary deposits it is the rule to find the marine shells almost unchanged by the addition of mineral matter, and in general it may be added that the older the organisms are geologically, the more mineralized they are apt to be. Probably 50 per cent of all fossils still remain in their original calcareous condition or are but slightly permineralized. This mineralization may take place through the waters percolating in the rocks at any time after the entombment of the fossils or during the time of weathering of the formations, but it is more apt to have occurred during the time of burial, when the ground waters of the sea-floor were charged with carbonic and other acids derived from organic decomposition. For these reasons, the fossil skeletons of organisms occur in all conditions from the unchanged to complete pseudomorphs in calcite, dolomite, silica, iron pyrite, or even lead, zinc, etc.

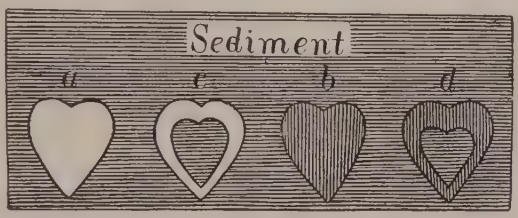


Fig. 321. — Diagram to illustrate molds and casts. The horizontal lines represent sediment, and the vertical ones the subsequent filling. *A*, the natural external mold of a bivalve with the shells removed by solvent waters. *C*, the same shell, but having the original cavity filled with sediment = natural internal mold. *B* and *D*, the molds filled by solvent waters with foreign materials = a cast and a pseudomorph.

Again, the percolating land waters or the ground waters of the sea may have dissolving powers only, and remove all of the organic shells; in this case their former presence is indicated by cavities in the rocks, the molds of organisms, more commonly seen in dolomites and sandstones. These molds are often so wonderfully sharp that the finest artificial casts or squeezes can be made from them. On the other hand, it often occurs that molds, and especially those in dolomites, are covered with a lining of crystallized mineral matter, in which case the fossils are nearly always valueless. Even though molds are bulky to collect, nevertheless they should be gathered, and the casts on the inside of them, the filling of the interior cavities of the organisms, should be secured as well. Imprints

are more commonly seen in the shales and are the impressions in mud of the exterior parts of plants and animals.

Where Fossils Occur. — Fossils are to be especially looked for in the evenly bedded strata of marine origin that are more or less calcareous or magnesian, and least of all in the red shales and sandstones. In nearly all of the red beds other than red limestones it is the exception to find fossil remains, because the plants and animals have been oxidized and dissipated during the process of subaërial sedimentation. It is therefore the green, blue, gray, black, and subsequently oxidized yellow beds that are apt to hold fossils. However, the red shales and sandstones may also have such fossils as the foot imprints or trails of animals, very rarely the bones of vertebrates, and still less often the imprints of plants or chalcedonized woods. In fresh-water deposits fossils are usually very scarce, but subsequent to the Silurian such beds may have plant and vertebrate remains.

Of all stratified rocks, shales make up 80 per cent, sandstones about 15 per cent, and limestones 5 per cent. It is in the limestones that fossils are nearly always present in abundance, but this does not mean that for every foot of limestone, nine of the shales and sandstones are barren of organisms. Carbonate of lime is widely disseminated throughout the strata, and in all the calcareous shales there are apt to be fine fossils that will weather out free; even the calcareous sandstones usually have organisms in some abundance. Further, the thick green and blue shale formations often have thin beds of impure limestone or sandstone and in these bands fossils should be looked for.

Conglomerates may abound in fossils, but here especial care must be exercised in keeping apart the specimens of each pebble, as these may be of very different ages. The fossils of the matrix also must not be mixed with those of the pebbles, for otherwise an impossible chronogenetic association will result. On the other hand, the breccias and intraformational conglomerates have the same species as the binding matrix, because all were formed at the same time.

How Fossils Are Collected. — In looking for fossils there should be no haste, as the work of collecting is always a slow process. It seems to be a common opinion that paleontologists " scent " the presence of fossils, a conclusion that is wholly erroneous, for they are often discovered only after patient hunting.

On any exposure of stratified rocks fossils may occur, and therefore the surface should be scanned for loose specimens. These free fossils are the most desirable because they require the least labor in cleaning, and, further, they show all parts

of the individual. All residual red clays should be searched, as these are often replete with fine free specimens, usually preserved in silica as pseudomorphs.

When loose fossils are found, trace these to the bed from which they come and while doing so note the occurrence of others still in place. Naturally the best places to find fossils are in the hard protruding ledges of limestone, and all such should be broken here and there with the hammer. Sometimes a thin zone will be one mass of fossils, and when weathering has loosened them so that they will fall out freely when hit by the hammer, the easiest way to collect such is to take away a lump from 6 inches to a foot across. In this connection it should be added that weathered rock yields fossils far more easily than that not so affected.

Fossils of a siliceous nature and partially weathered out of limestone should be gathered in bulk, to be treated in the laboratory with dilute muriatic acid (Fig. 317). Material which will bear this treatment is readily tested in the field with a pocket knife; if the blade does not scratch the fossil, but leaves a black mark, it will be well to make the experiment. Of course where the fossils are in cherts or are more or less surrounded with amorphous silica, nothing can be done to free them.

The field geologist in collecting fossils for study by the paleontologist will do well to remember that the value of the work of the latter depends largely on the number of specimens he can study, and therefore as much material as circumstances permit should be gathered. It is not so much a quantity of specimens, however, as it is of species that a paleontologist desires, because it is known that different forms have very different chronogenetic values. As a rule, the more abundant a species, the less its stratigraphic significance.

CHAPTER XX

THE GEOLOGICAL TIME-TABLE

Rise of Classification. — Geologic classification had its origin in the "formations" of two German geologists, Lehmann (1756) and Füchsel (1762); hence our present knowledge of the succession of formations, now called periods, and of the grouping of these into eras of time, is the result of one and a half centuries of endeavor on the part of the geologists of western Europe and America. Even so, we are far from a completely determined chronology.

The older geologists had, in general, no clear ideas of the geographic extent of geologic formations, but Werner (1775–1817), professor of mining at Freiburg, Germany, had such a conception, and on the basis of some facts and much fancy he taught with wonderful success that the formations were universal for the earth; and to this day Geology has not completely divested itself of this fallacy.

Geology was at first a science of minerals and rocks, and it was not until the significance of fossils as determinants of age was first worked out in England by Smith (1799–1801), and still more clearly by Cuvier and Brongniart in France (1808–1811), that stratigraphy and geologic chronology had their beginning. Cuvier taught that each formation contained its own *specially created* flora and fauna, and that each creation was in turn *destroyed by a general catastrophe* (see also page 5). Geologists were largely swayed by these ideas until the appearance of Darwin's famous book, *The Origin of Species*, — although Lyell (the great Uniformitarian) had long previously combated the theories of the catastrophists — when they gradually came to see that life had been continually present and evolving into other forms. The idea of catastrophism has now given way to the theory of local and general changes in the environment, changes that bring about small and great alterations in the plants and animals and in their local associations. We learn, therefore, that the primary basis for discerning the sequence of geologic events is the fossils entombed in the rocks at the time of the formation of the latter. However, many rocks have no fossils, and in the earlier and longer portion of the earth's history the life

then existent was so rarely preserved that other methods have had to be devised to unravel their sequence and genetic relation to one another. These various principles will be described later in this chapter, beginning with the criteria (standards of judgment) of the fossils and then proceeding with those of oceanic spread, erosion, and diastrophism.

The Geologic Column

Here will be introduced the geologic column or time-table, which gives the sequence of the time terms as they will be used throughout this book. These terms are expressive of ideas — for example, Mesozoic for medieval life — or are geographic names, taken as a rule from the area where the formations were first studied — for example, the Comanchian of Texas, from the home of the Comanche Indians. These latter localities hence have become the typical areas with which all other localities having rocks and fossils of the same age must be compared (correlation). The origin and meaning of all of the terms will be explained in the proper places, and the student is urged to commit to memory at least all of the information and particularly the succession of the terms in the three columns on the left of the tables. This knowledge is the *A*, *B*, *C* of Historical Geology, and without it further progress is almost impossible.

GEOLOGIC CHRONOLOGY FOR NORTH AMERICA

(1) Classification Based on Superposition of Strata, and Erosion Intervals

Correlation by Means of Fossils

Eras	Major Divisions	Periods	Epochs		Advances in Life	Dominant Life
PSYCHOZOIC			Recent (Alluvial or Post-Glacial)	Cascadian Revolution	Rise of world civilization The era of mental life	AGE OF MAN
CENOZOIC (Modern Life)	Quaternary	Glacial	Pleistocene		Periodic glaciation Extinction of great mammals	AGE OF MAMMALS AND MODERN FLORAS
	Tertiary	Late Tertiary (Neogene)	Pliocene		Transformation of man-ape into man	
			Miocene		Culmination of mammals	
		Early Tertiary (Paleogene)	Oligocene		Rise of higher mammals	
			Eocene		Vanishing of archaic mammals	
MESOZOIC (Medieval Life)	Late Mesozoic	Epi-Mesozoic Interval		Laramide Revolution	Rise of archaic mammals	AGE OF REPTILES
		Cretaceous	Lance		Extinction of great reptiles	
			Montanian Coloradian		Extreme specialization of reptiles	
		Comanchian			Rise of flowering plants	
	Early Mesozoic	Jurassic			Rise of birds and flying reptiles	
		Triassic			Rise of dinosaurs	

GEOLOGIC CHRONOLOGY FOR NORTH AMERICA (*Continued*)

Eras	Major Divisions	Periods	New Periods		Advances in Life	Dominant Life
PALEOZOIC (Ancient Life)	Late Paleozoic or Carboniferous	Epi-Paleozoic Interval		Appalachian Revolution	Extinction of ancient life	AGE OF AMPHIBIANS AND LYCOPODS
		Permian			Rise of land vertebrates Rise of modern insects and ammonites Periodic glaciation	
		Pennsylvanian			Rise of primitive reptiles and insects	
		Mississippian	Tennesseian		Rise of ancient sharks	
			Waverlian		Rise of echinoderms	
	Middle Paleozoic	Devonian			Rise of amphibians First known land floras	AGE OF FISHES
		Silurian			Rise of lung-fishes and scorpions	
	Early Paleozoic	Ordovician	Cincinnatian		Rise of land plants and corals	AGE OF HIGHER (SHELLED) INVERTEBRATES
			Champlainian		Rise of armored fishes	
			Canadian Ozarkian		Rise of nautilids	
		Cambrian	Croixian		Rise of shelled animals	
			Acadian		Dominance of trilobites	
			Waucobian		First known marine faunas	

GEOLOGIC CHRONOLOGY FOR NORTH AMERICA (*Continued*)

Pre-Cambrian History (After Barrell)

Archean of Earlier Authors

(2) Classification Based on Sequence of Rocks, Crustal Movements, and Cycles of Erosion
Order of Events According to Coleman

Correlation without the Aid of Fossils

Eras	Major Divisions	Periods		Physical Characters	Dominant Life (Inferred)
		Recorded dominantly by surface deposits (Sedimentary and igneous)	Recorded dominantly by internal structures (Intrusion and diastrophism)		
LATE PROTEROZOIC (Primitive Life)	Algonkian	**Great Epi-Proterozoic Interval. Over much of the earth the unconformity extends to Algonian Revolution**			
		Keweenawan		Continental sediments and basic volcanics Metalliferous deposits in older rocks	**AGE OF PRIMITIVE MARINE INVERTEBRATES**
		Animikian		Marine sediments dominant Great Iron Series	
				The Eparchean Interval of Lawson	(Fossils almost unknown. Delimitation of base of this age indefinite)
		Huronian		Aqueous and glacial deposits Oldest known fossils	

GEOLOGIC CHRONOLOGY FOR NORTH AMERICA (*Concluded*)

Eras	Major Divisions	Periods		Physical Characters	Dominant Life
EARLY PROTEROZOIC (PRIMITIVE LIFE)	ARCHEAN OF LATER AUTHORS — NEO-LAURENTIAN	**Ep-Algomian Interval. Peneplanation of mountains and continents**			**AGE OF PRIMITIVE MARINE INVERTEBRATES** (*Continued*)
			Algomian Revolution	Bathylithic mountain-building Metamorphism and igneous invasion of Sudburian and older rocks	
		Sudburian		Basic lava flows in upper part Conglomerates and quartzites dominant (Temiscaming, Pontiac, etc.)	
ARCHEOZOIC (PRIMAL LIFE)	PALEO-LAURENTIAN	**Ep-Archeozoic Interval. Profound erosion of mountains and continents**			**AGE OF UNICELLULAR LIFE** PROTOZOA AND PROTOPHYTA (Fossils unknown)
			Laurentian Revolution	Bathylithic mountain-building Igneous invasion of Keewatin Crustal disruption	
		Keewatin Coutchiching Grenville		Basic volcanics and iron formations Coutchiching schists and gneisses Grenville calcareous sediments	

THE UNRECOVERABLE BEGINNING OF EARTH HISTORY

COSMIC HISTORY

Basis of Chronology. — The fundamental principle underlying all endeavor to make out the geologic past is evolution, the oscillating but progressive changes wrought in the long ages, changes whose interpretation leads to the history of the earth — the science of Historical Geology.

The earth develops as a whole, but the record is far from being everywhere alike; even if it were so, it would not be wholly accessible for study, because sheet upon sheet of rock hides others below, and the atmospheric agencies have destroyed much through erosion. Likewise, the more complete stratigraphic record buried under the oceans is hopelessly lost. Therefore the completed geologic record will eventually be put together from the evidence of all places which are at present land, mainly, however, from the northern hemisphere, because this is preëminently the land hemisphere. Such history is largely brought about through the periodic adjustments of continental and oceanic areas settling down upon a shrinking nucleus, and in so doing crushing the outer shell into great folds which tend to rise, especially upon the margins of the continents. Broad movements of a vertical nature also take place at times, whereby the continents, being underlain by lighter rock matter, tend to warp up and restore the elevations destroyed by erosion, while the floors of the sea, loaded with sediment, tend to sink, as explained under isostasy (page 250).

Evidence of Fossils

Fossils furnish the first step in the process of stratigraphic correlation. Their testimony is checked by the geographic distribution of the sediments that contain them, and by the relation of the latter to the formations beneath and above them (superposition). These principles are easy to state but very difficult to apply accurately to so great a land mass as North America, and even though approximately a century of work has been devoted to it, the ground is only about half covered by detailed studies.

Changing Environment. — In general, sedimentation is a slow process, and under relatively constant surroundings, it is held that but little if any recognizable change in the species is developed, but as the environment of the organisms is continually changing, even though only to a minor extent, these physical alterations cause the faunas at the very least to alter their combinations and to shift from place to place. They die out in one area, but gain a foothold elsewhere, and although this to-and-fro migration is slow when measured in years, yet in stratigraphy the faunal

assemblages appear as if suddenly introduced. This fact has always excited the interest of the paleontologist, and he has explained the phenomenon according to the view of his generation. Once he thought it due to special creations of new types or recoinages of old, but since the time of Darwin it has been looked upon as due to slow evolutions of which glimpses only are obtained in the fragments of the geologic record; or it may be due to shiftings of faunas, or to geologically sudden migrations into the continental or interior seas from the permanent or outer oceanic reservoirs, the continuous realms of marine organic evolution. The fossil faunas from the oceans spread as fast as the sea transgressed the land, and, for practical purposes in stratigraphy, they may be accepted as having appeared simultaneously in widely separated places.

Different Values of Different Fossils. — The localized species (forms restricted to a locality) are of the greatest value in the stratigraphy of small areas, while the new forms which attain wide dispersal are on the other hand of most significance in correlating the time stages in separated regions, for they are progressives, the time heralders, as distinguished from their variously conservative associates. Therefore in the chronologic correlation of the stratified rocks most dependence is put upon a few species, known as " guide fossils," together with the collateral evidence of associated forms.

Dissimilarity of Successive Faunas. — Locally successive, but distinct, geologic faunas derived from the same oceanic realm usually exhibit a more or less ancestral or direct genetic relationship with one another in their structure. In some cases they are the returning, slightly altered descendants of an older fauna, in other words, " recurrent faunas." Therefore the possibility of a " break " in sedimentation between such superposed faunas is easily overlooked and the time value of the recurrent faunas underestimated. Or, two locally superposed faunas may be totally dissimilar, not only in the species but even in the majority of the genera, and yet the time break between them may be a comparatively short one, the reason for this unlikeness being that the two faunas are transgressions, that is, are migrations from different oceanic realms and have therefore had a development from different ancestors.

Three Faunal Aspects of a Period. — A geologic " period " begins as a time of quiet, following a disturbance and uplift of the land. The time of quiet is marked by the erosion of the land and the spread of shallow seas. Waterways broaden and unite across

a continent, only to be drained and destroyed by the crustal unrest with continental uplift which marks the close of periods. During the middle age of the periods, when the oceanic transgressions are greatest, the faunas throughout a continent are most alike in composition and have the greatest number of species in common; these are the " cosmopolitan faunas." Again, faunas of the same age are most dissimilar in the early times of the periods, when the oceanic realms are most confined to certain regions, and the transgressions of the waters upon the continents are smallest. Restriction also takes place during the closing age of the periods, though at these times there are many more hold-over species from the earlier, widely dispersed faunas; in other words, there is no marked introduction of new organic types during the recession of the continental seas. However, when the oceans again spread over the continents, a long time will have elapsed, many of the old familiar forms will have disappeared under the stress of restricted habitat, and new forms will have been developed, the prophets of a new period and indicative of the next trend in evolution.

Physical Evidence

Evidence of Periodic Oceanic Spreading. — Another primary principle of value in marking the periods of geologic chronology is the recognition of the times when the surface of the earth and the oceanic level are in decided motion. It is now clear that North America has been more or less widely flooded by the oceans at least fifteen times since the Proterozoic era, and the other continents have been similarly flooded many times. The movement of the oceans may be of small and narrow extent, as the result of horizontal compression (local or orogenic); or its horizontal and vertical effects may be felt over areas of great magnitude (epeirogenic). Not only do the lands move up and down, the sum of this motion being in the main upward (positive movements), but it is also now clear that the ocean bottoms are periodically more or less in motion, with the sum of their movements downward (negative movements). For these reasons, the oceanic level in relation to the continents is inconstant, and therefore the marine spreadings over the lands, with their concomitant sedimentation, are not only variable in time, but also in geographic extent. On the other hand, when the lands protrude more than usual above the strand-line, the oceans naturally overlap the continents least widely and make at such times limited marine stratigraphic records, which are restricted to the margins and their embayments and to

the persistent axes of depressions, the geosynclines of the continent. As the oceans and seas are all connected one with another, and are also the receivers of most of the land wash or detritus, it follows that a displacement of the strand-line anywhere, through any cause, must be transmitted to all marine waters. It has been calculated that if the protuberant land masses were transferred to the oceans, the general sea-level would be raised about 650 feet, and therefore the North American continent would be flooded to a depth of at least several hundred feet. Then under the waters there is continuous sedimentation, and they abound in more or less of evolving life that is most advantageously situated for burial and preservation; hence the marine stratigraphic sequence is the least broken of the several kinds of historic records accessible to geologists.

It is now known that the oceans have spread periodically and more or less widely over the North American continent, the areal extent of which is about 8,300,000 square miles. These floods occurred hardly at all during the Cenozoic, 1 per cent to 6 per cent of the continent being then covered; four times widely during the Mesozoic, the submergences reaching from 3 per cent to 33 per cent; and, with the maximum spread, apparently twelve times during the Paleozoic, when 1 per cent to 47 per cent of the continent was flooded. More broadly it may be stated that the floods begin and end with shelf seas marginal to the continents and varying in extent between 1 per cent and 5 per cent of the total areas of the continental platform, the conditions being thus not unlike the present conditions of overlap; while the greatest inundations during the middle of the periods attain from 12 per cent to 47 per cent of the continent.

It is therefore apparent why the major portion of the earth's chronology depends for its determination upon the marine sediments. These formations, except in so far as they are later eroded, record the extent of the transgressions, and, in their physical characters, something of the topographic form of the adjacent lands, with a hint as well of their climates; and through their fossils they establish the chronology from place to place. However, this is by no means all, for the newer geology also teaches, as we have seen, that the strand-line is constantly and geographically irregularly in motion, either very slowly transgressing more or less of this or that land, or receding as the lands emerge. Therefore, in no one country is there a total record, but everywhere the story is more or less incomplete, and our chronology is but a patchwork of all the

local histories pieced together into one still very imperfect geologic time-table.

In the marine formations we are, then, everywhere dealing with oceanic *overlaps* whose records for the time being were more or less complete, but each series of beds is also nearly everywhere separated from the adjacent ones by erosion intervals. The latter are due to the periodically recurring emergent times in the history of the continents, which may be either local or of wide extent, the marine records in the latter case being swept away by atmospheric agencies.

Evidence of Erosion. — Geologic chronology has been so far almost wholly, though necessarily, interpreted on the basis of stratified rock accumulations, that is, the marine and continental strata. There is, however, still another record that has so far been almost refused recognition in our time-tables. This is the time evaluation of topographic form at any given stage of development (the physiography of the present, the paleophysiography of the past). To be sure, it is mainly a condition of removal by erosion of previously made histories, but nevertheless the topographic form of the land still remains and has a time value. We all appreciate to a certain extent the significance of unconformities as records of emergence and erosion between periods of inundation, but can any one tell what time value is to be accorded to the complete removal to sea-level of mountain ranges like the present Alps of southern Europe? Many times have similar mountain chains been washed away and then rejuvenated by upwarp to some extent, only to be worn away again after each reëlevation.

Evidence of Breaks. — The erosion intervals are the "breaks," the "lost intervals," or the disconformities in the succession of strata. In addition to the disconformities, there are unconformities due to movements in the shell of the earth when mountains are made (see page 288 *et seq.*).

The breaks are known to be many, but they are far greater in number, and their time durations, although admittedly very variable, are far longer than is usually believed to be the case. The geologic column will probably never be completed on the basis of the recoverable physical and organic evidence, but it will grow into greater perfection for a long time, and this growth will come through the discovery of formation after formation along the lines of these breaks, and more particularly in the areas nearest the continental margins. The perfection of the column will also bring about a greater harmony in the very variable estimates as

to the age of the earth, as given on the one hand by the geologists and on the other by the physicists.

The major breaks in the geologic record are indicated in the time-table by " intervals," the marked erosion periods representative in the main of wide and high continents and of dominant erosion, not recorded by sediments within reach of observation; therefore, in geologic chronology these are " lost times " of long duration. It was not thought desirable to give a new and independent name to each one of these intervals, but rather to use in modified form an old and familiar one. Therefore the Greek word *epi* (upon or after) is here adopted as a prefix to the era terms, to indicate the subsequent time, that is, the intervals. These intervals will then be known as *Epi-Mesozoic*, *Epi-Paleozoic*, *Epi-Proterozoic*, *Ep-Algomian* and *Ep-Archeozoic*. This method of naming was first proposed by Lawson. The same combination can be used, when it becomes necessary, for the intervals between the periods, as *Epi-Silurian*, etc.

Diastrophism

Means of Determination. — As shifting of the strand-line is the most important criterion in ascertaining diastrophic action (a term to include all movements of the outer parts of the earth), it is well to state here briefly how these alterations are most readily determined. Organically they are recorded: (1) by abrupt changes in the superposed faunas, and (2) by the sudden appearance of newly evolved stocks; physically, (3) by more or less obvious breaks in the sedimentation, due to sea withdrawal, (4) by change in the character of the deposits, especially when this involves abrupt transition from organically formed strata (marl, chalk, limestone, dolomite) to mudstone and sandstone, or a change from continental to marine deposition, and (5) by marine overlaps upon rocks of earlier age, producing typical unconformities.

Correlation of formations in separated regions is made in part also on a physical basis. This is done by finding similarities in disconformities (time breaks in conformably superposed or parallel strata, see page 292 and Fig. 243), and changing petrologic characters. A physical correlation is in general, however, far less reliable, and must ever remain second in importance to correlation by fossils for the discernment of diastrophic action. Of course, the most easily determined crustal movements are those which are compressive in character and lead to mountain-folding. Upon erosion and subsequent sea invasion, these angular or structural unconformities are the most easily found and those about which there can be the least doubt. The broad and gentle flexures known as crustal warpings, on the contrary, as a rule bring about the disconformities.

Periodic Movement of Strand-lines. — The crustal oscillations of the earth are not due to heterogeneous and unrelated movements, but are connected, in that areas of elevation and depression remain positive or negative throughout the eras, or during more or less long stretches of geologic time.

The major crustal deformations are periodic in appearance, and their visible areas of movement are now in this continent, now in another; and it is this periodicity which conditions geographic history and organic evolution. All of these active and decisive movements are of long duration, and their major work is confined to the marginal areas of the continents. Farther inland, new axes or depressed folds may rise or old ones be accentuated, and so divide the continental basins into a series of smaller water-ways. Not only are the margins of the continents elevated, but apparently at the same time the oceanic basins are made either deeper or larger, or both. This simultaneous movement of the oceanic bottoms and the continental margins is proved by the fact that the major crustal deformations occur during the emergent times of the geologic periods, and this is true, not only for the continent undergoing deformation, but also for other land masses which have not moved at all, but whose strand-lines have been lowered in consequence of the oceanic enlargement.

The long-enduring middle portion of the periods is marked by relative crustal stability, as shown by more or less reduction of the continents to sea-level (peneplanation). The sediment from the eroded lands adds that much volume to the sea and causes its level to rise as a result of the partial filling. This effect, accompanying the general leveling of the land surface, produces, in the middle of the periods, maximum sea invasion. On the other hand, the earlier times of each cycle exhibit less crustal constancy and more marked erosion. The lands then warp more or less along predetermined lines, due to internal adjustments following the major movement and the reëstablishment of the balance between the sinking and rising areas (isostatic balance or isostasy), which has been altered by those deformations, by the sea invasion, and by the unloading of emergent land areas into the seas of the continents. During the closing stages of the periods, there is a renewal of crustal unrest, seen in the vanishing of the continental seas, which finally ends in another major crustal movement and in more or less complete withdrawal of the seas from the lands.

Rhythm of Strand Movements. — There is a certain amount of rhythm in these periodic movements and this meter permits us

to group the formations into systems or periods. The more active introductory orogenic movements are of comparatively short duration. In contrast, the quieter but broader deformations within the period, of epeirogenic nature, as shown by the world-wide movements of the strand-lines (eustatic movements), are of long continuance. Each submergence with the following emergence is seemingly the natural basis for the delimiting of a period. Among these periodic movements some are far more intense and of greater geographic extent than others, at times when mountain ranges in more than one continent are simultaneously or successively in motion. These are the diastrophic grand cycles, or, according to Dana and Le Conte, the "critical periods" or "revolutions" in the history of the earth, and they divide, as it were, the book of geologic time into chapters.

Terminology

Formations and Periods. — The local warpings as a rule bring about the development of formations and disconformities. These are grouped together into the periods by the "minor diastrophic movements," when local mountain ranges are developed. As there are many of these movements and as they are not of the first order of magnitude, it is proposed to call them *disturbances*, to distinguish them from the rarer but far greater events, the "major diastrophic movements," or *revolutions*, which group the periods together into eras.

It seems probable that the periods were all separated by disturbances, events occurring now in this and now in that continent, but in each case enlarging some oceanic basin and so reacting on the strand-line the world over. On the other hand, during the revolutions, all of the oceans were enlarged by the sinking or broadening of their basins, and all the continents were more or less reëlevated. These latter times are the critical periods in the history of the earth.

Critical Periods and Eras. — The critical periods are marked by the following features:

(1) By wide-spread deformation of the earth's crust, transmitted from place to place. This leads to the elevation of many and widely separated mountain ranges, followed by long intervals of erosion and mountain removal, and therefore by almost universal unconformities. Because of the long-enduring intervals of lost record, the subsequent faunas are not only very different, but appear as if suddenly or at least quickly evolved. Each revolution or critical period is named after one of the prominent mountain ranges formed at the time designated, for example, Laramide and Appalachian revolutions. The subsequent interval is the transition period from one era to the next.

(2) By wide-spread changes in the physical geography. That is, there are at these times a highly diversified or young topography, decided alterations in the continental outlines, the making of new or the breaking down of old land connections (the land bridges which permit intercontinental organic migrations), and marked changes in the oceanic currents, all of which also lead to marked variations of temperature and often to actual glacial periods.

(3) By marked and wide-spread destruction of the previously dominant, prosperous, and highly specialized organic types. This is produced partly by the physical changes and partly by the extensive migrations that are more conspicuous at these times and that therefore invite the spread of death-dealing parasitic diseases.

(4) By the marked evolution of new dominant organic types out of the small-sized and less specialized stocks, and by the development of hordes of new species.

The last or Cascadian Revolution is so recent that the record of it is not lost, and a study of this enables us better to comprehend the changes wrought by the earlier revolutions. Le Conte regards it " as the type, as the best proof of the fact of critical periods, and as throwing abundant light on the true character of such periods, and especially on the causes of the enormous changes in organic forms during such times."

Period Names. — The periods usually take their names from the geographic area where the system of rocks was first considered to be of period value. Thus the Cambrian, Ordovician, Silurian, and Devonian systems were first discriminated in England and Wales, and take their names from ancient peoples living in these countries, or from the district in which the rocks are best developed. Mississippian directs attention to the Mississippi valley, where these rocks are best represented. Triassic has reference to the tripartite development of rocks of that age in Germany, and is an heirloom from the days of Geology when the science had not worked out the principle that formations and periods must be based upon type areas. Cretaceous is a still older inheritance from the days of mineral Geology, the name being based upon the chalk deposits of western Europe.

The Final Geologic Time-table

The time is not yet at hand for a complete evaluation of the minor diastrophic movements, because the recorded geologic succession in the different countries is by no means the same. For instance, the chronology of Africa south of the Sahara Desert is in the main one of erosion, with a wonderful record of continental deposits and glacial formations. In other words, this continent throughout time has generally stood well above the pulsating oceans, and owing to reëlevation in recent geologic periods now stands at an average elevation of 2000 feet above sea-level. North America, on the other hand, lay near sea-level throughout the

Paleozoic, was often in part submerged, and therefore has recorded in its rocks the most complete history of this era; but during the Mesozoic the greater part of the eastern half of the continent was continually above the sea. The Mesozoic marine sedimentary record is, in consequence, restricted to a narrow strip along the Atlantic, to a wider area along the Gulf and Pacific margins, and to the Great Plains country, over which there flowed great inland seas from Mexico to the Arctic in Cretaceous time. To find the Mesozoic history in greater perfection we must look to the countries to the north of the Mediterranean. On the other hand, the Ordovician period is closed in America by the Taconic Disturbance (named from the Taconic Mountains of eastern New York), when low mountains were thrown up from Virginia to Newfoundland, whereas this movement is hardly registered in Europe outside of Great Britain (see also page 636).

Because of these unsatisfactory conditions in our present knowledge of the earth's history, it cannot be stated that the periods in the accompanying table are the only ones that will eventually be recognized in North America. On the contrary, we confidently expect to see evidence developed to show that the Mississippian period embraces two diastrophic cycles or periods (Tennesseian and Waverlian); the Ordovician has apparently four (Cincinnatian, Champlainian, Canadian, and Ozarkian); while the Cambrian also has three (Croixian, Acadian, and Waucobian). To keep these movements or probable diastrophic cycles of period value before geologists, their names have been placed in the fourth column of the table.

In conclusion, it may truthfully be said that there is now a good deal of harmony among geologists in their use of the theory that the surface of the earth is periodically and rhythmically in motion, and that this diastrophic action is the basis of chronogenesis, developing not only cycles of sea invasion and land emergence, and cycles of erosion, but also cycles of organic evolution. Although the eras are clearly recognizable everywhere, nevertheless, until the geologic geography of Europe is worked out in detail, we shall not be able to say that the various *periods* in current use are all established in nature, and it will therefore doubtless be advisable for America to continue to work out her own geologic chronology.

A geological map of North America will be found at the end of this book.

CHAPTER XXI

THE LANDS AND THEIR LIFE

The earth is one of the minor planets attendant upon the sun, and because of the small mass of all the planets, it is under the full gravitative control of the central solar body. The earth is dependent on the sun for practically all of its heat and light, and through these, for nearly all of the activities that have given character to its history. However, another not inconsiderable source of energy is found in the interior of the earth itself (see also page 8).

The Spheres of the Earth. — The vast central mass of the earth, the *centrosphere*, consists of unknown material surrounded by a thick earth-shell, the *asthenosphere*, marked by a capacity to yield readily to long-enduring strains of limited magnitude (Barrell). In other words, the latter sphere is the one of earth weakness, the zone of yielding matter between the firm centrosphere and the outer rocky envelope spoken of as the *lithosphere*. The two outer spheres are together known as the *pyrosphere*, because they have more or less of molten rock. Lying upon the lithosphere, and to a very limited extent circulating within it, is the *hydrosphere* or sphere of water; and outside of all is the sphere of gas and vapor known as the *atmosphere*. Within the hydrosphere, above the surface of the lithosphere, and at the base of the atmosphere exists the *biosphere*, consisting of the living organisms, the plants and animals. Collectively the organisms are also spoken of as the bios, and of the parts of this bios as it changes in the course of geologic time much will be said in subsequent chapters.

The Atmosphere: a Thermal Blanket. — Le Conte has well said that the atmosphere is a kind of blanket put about the earth to keep it warm. So far as life is concerned, this is one of the most important functions it has, though its importance is great in other directions also. The reason for this is that the air is transparent to those rapid vibrations of ether received from the sun which we know as light. On reaching the ground, however, a considerable portion of the light is transformed into much slower vibrations, which we perceive as heat. Now if there were no atmosphere, these heat vibrations would pass off into space and be lost; the result would be that the burning heat of the unmodified sunlight

would be turned into almost the intense cold of outer space at night. This is prevented by the atmosphere, which retains the heat and thus moderates and equalizes the temperature on the surface of the earth. Of the various gases which compose the atmosphere (see page 9), the oxygen and nitrogen are transparent to both the quick light vibrations and the slower heat ones; they could not therefore alone modify temperature in any great degree. The carbonic acid gas and especially the water vapor in the air, on the other hand, while transparent to light, are more nearly opaque to heat vibrations, and it is due to them that the heat is retained. The larger proportion there is of them in the air, therefore, the more equable will be the temperature. This explains why deserts, with their dry atmosphere, suffer such changes of temperature between day and night, while the moist atmosphere of oceanic islands gives them such even climates.

It must not be understood that all sunlight is thus turned into heat, as a portion is absorbed in passing into the atmosphere and another part is reflected back as light and not transformed; it is the remaining portion that is thus effective.

Variable Conditions in the Past. — As a thermal blanket the atmosphere has varied much throughout geologic time. In general, it may be said that the temperature of the air and water has been for long stretches of time fairly equable and genial over most of the earth. Periodically, however, the lands have undergone a severe reduction of temperature and were then more or less widely covered with snow and ice. These cold climates have also reacted on the temperature of the oceans, both because there is less heat in the oceanic waters and because into them are poured the cold waters derived from the lands. In this way the genial climates of the lands and oceans have been changed many times to cool and even cold. At least five cold times in the history of the earth are now known, and it is probable that even more will be discovered.

All of the colder climates fall in with the times when the continents are largest and highest. On the other hand, it is very probable that the climates have very often fluctuated between warm and moist and cool and more or less arid. This conclusion is derived from a study based in the main on the nature of the plants and animals living at any given time, and is further strengthened by the nature of the associated geologic deposits and the degree to which the oceans have from time to time covered the lands. These alterations — and there are many of them — will be pointed out in their proper places.

The Lithosphere

Size. — The *lithosphere* has a polar diameter of about 7899 miles, and an equatorial diameter of about 26.8 miles more. The surface area of the earth, according to Chrystal, is 196,940,000 square miles. Of this, 69.6 per cent (137,000,000 square miles) is covered by water, and 30.4 per cent (59,870,000 square miles) is dry land (Murray, 1912). In the northern or land hemisphere the area above sea-level is about 41,112,000 square miles, while in the southern or water hemisphere it is only about 16,142,000 square miles. It is very important to bear in mind this relation of water area to land surface, because any alteration in the lithosphere or hydrosphere not only reacts on the shape of the continents but more especially changes the totality of their surficial area.

Relation of Continents to Oceans. — The surface of the lithosphere departs from a spheroidal form because the *continental platforms* (see page 251) protrude above the general level of the sea, while the bottoms of the oceanic basins lie below it. The continents are, however, more or less submerged about their margins, and the area under water down to the 100-fathom (600 feet) line is truly a part of the continents, because it is only beyond this that the descent is rapid down the continental slopes into the oceanic depressions. For more detail and diagrams see pages 82 and 103. These marginal shallow-water areas are known as the *continental shelves*, and have an areal extent of less than 5 per cent (9,770,000 square miles, according to Murray) of the earth's surface. Therefore, the continental platforms have an area of 35.5 per cent of the lithosphere, while the remainder, 64.5 per cent, is occupied by the depressed oceanic basins.

The relative areas of the lithosphere above and below sea-level are as follows:

	Per cent	
The highest peak is Mt. Everest in the Himalayas, 29,000 feet		
More than 6000 feet above sea-level	2.3	Land area 30.4 per cent
Between sea-level and 6000 feet above	28.1	
Between sea-level and 600 feet below	5.1	Area of continental platform 35.5 per cent
Between sea-level and 6000 feet below	7.0	Water area 69.6 per cent
Between 6000 and 12,000 feet below	14.8	
Between 12,000 and 18,000 feet below	39.6	Actual oceanic basins 64.5 per cent
Between 18,000 and 24,000 feet below	3.1	
The greatest known oceanic depth is near Guam, 31,600 feet		

Oceans and continents are the grander divisions of the earth's surface, the continents being separate areas, while the oceanic basins are connected one with another and widely so in the southern hemisphere (see Fig. 323). The waters surround the large south-polar land *Antarctica*, and continue north in three great prolongations. Of these the *Pacific* is the oldest and the broadest (6000 miles across), then the *Antarctic* (really not separate from the other oceans), and next the *Atlantic* (North Atlantic 2800 miles in width), while the *Indian Ocean* is the youngest and smallest of these sunken areas. The lands are gathered about the small and shallow *Arctic Ocean* and extend south in two great aggregates, the narrow occidental lands (North and South America, averaging about 2200 miles across), and the broad oriental lands (Eurasia, with an average width of 6000 miles) (see Fig. 322). The latter land mass has, however, in Africa and Australia, two southern prolongations, making in all three, corresponding to the three oceans. Thus the continents and oceans interlock, the former narrowing southward, the latter northward.

Names of the Lands. — The lands are divided into six great geographic divisions, as follows: (1) *North America;* (2) *South America* (Fig. 324); (3) *Eurasia*, or combined Europe and Asia; (4) *Africa;* (5) *Oceanica*, comprising West Oceanica or Malasia, Central Oceanica or Australasia (Australia, Tasmania, New Zealand, and the Fiji Islands), and East Oceanica or Polynesia; and (6) *Antarctica* (Fig. 325).

Islands. — The islands adjoining the continents are properly *continental islands*, and are to be regarded as unsubmerged portions of the continental shelves, separated from the mainland. On the other hand, the *oceanic islands* rise from the depths of the ocean basins, and, as a rule, are volcanic accumulations on the ocean floor. For more detail see page 107.

Mean Elevation of the Land. — The mean height of the continents above the sea is given by Sir Archibald Geikie as about 2400 feet, and the mean height of them severally is about as follows: Europe, 1030 feet (area in square miles 3,700,000); Asia, 3300 (16,400,000); North America, 2100 (7,600,000); South America, 2100 (6,800,000); and Africa, 2100 (11,000,000). Dana says that the material of the Pyrenees spread over Europe would raise the surface only 6 feet; and that of the Alps, although of four times larger area, only 22 feet. Finally, only 6 per cent of the lands (or about 3,300,000 square miles) is 3250 feet above sea-level, so trifling is the total surficial area of the mountains.

The extremes of level in the land not covered by water are about 1300 feet *below* the level of the Mediterranean at the Dead Sea or the Sea of Sodom in Palestine, and 29,000 feet *above* on Mount Everest. For more detail see pages 251 and 252.

Continents

Characteristics of Continents. — Dana defines a continent as "a body of land so large as to have the typical basin-like form,

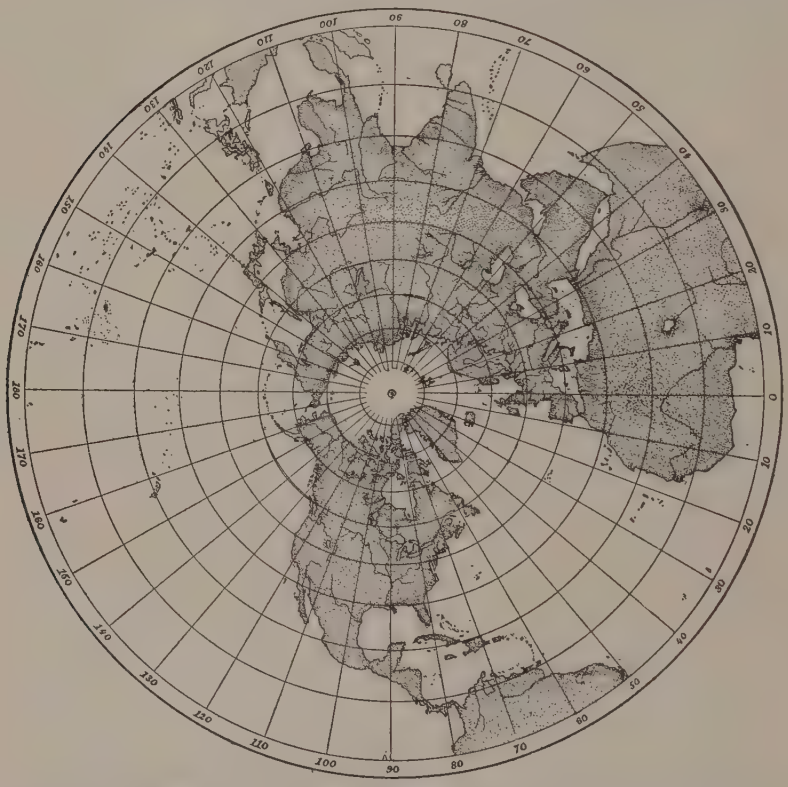


Fig. 322. — Stereographic map of the northern or land hemisphere, showing the lands centering around the Arctic Ocean. After Penfield.

— that is, independent mountain chains on either side of a low interior." As the mountain borders of the continents vary from 500 to 1500 miles in breadth at the base, it follows that a continent cannot be less than a thousand miles (twice 500) in width. The higher border faces the larger ocean; in North America the higher and wider Rocky Mountains face the Pacific Ocean, while

the narrower Appalachians margin the continent on the Atlantic side. Between them lies the continental basin, a vast area drained by the Missouri and Ohio, which flow into the Father of Rivers, the Mississippi. As the Arctic Ocean is small and comparatively shallow, North America in the far northeast is bordered by low and narrow mountains, known as the United States Range. On the south, the small Gulf of Mexico has its compensating elevations in the low Quachitas of Arkansas and Oklahoma.

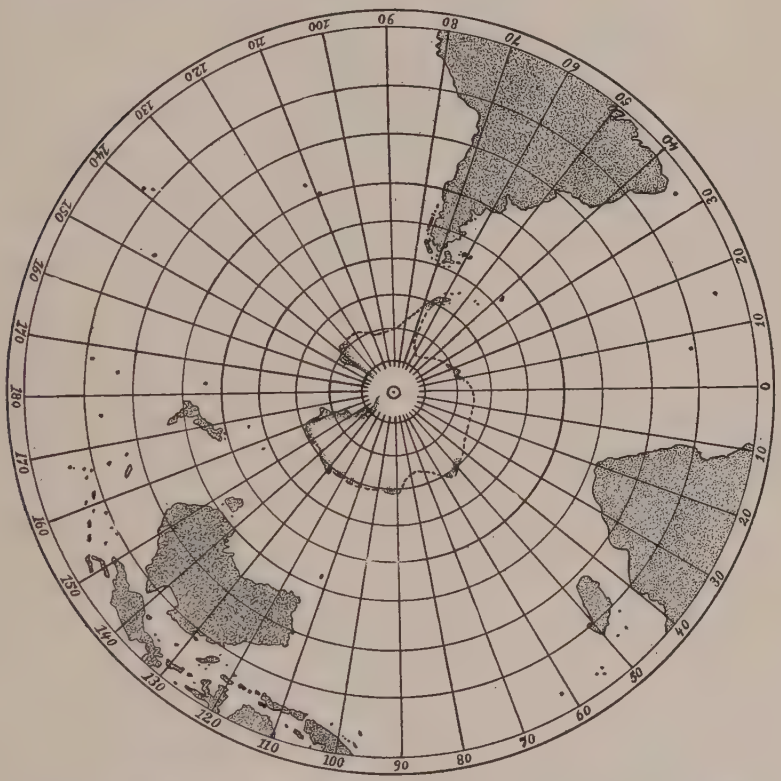


Fig. 323. — Stereographic map of the southern or water hemisphere, showing the south-polar land, Antarctica, and the three continental terminations, South America, Africa, and Oceanica.

The Nuclear Lands or Shields. — Most of the present continents have been formed around ancient protuberances of the lithosphere, the nuclear lands or shields. For the most part these consist of very old igneous rocks and metamorphosed sedimentaries. They are the oldest lands that have remained more or less continuously above sea-level. In general, however, these nuclear con-

tinental masses are not the areas from which the subsequent formations have derived their sediments, for nearly all of them have remained low in relation to sea-level. They appear to have come into existence certainly as early as Proterozoic time and as a rule furnish no fossils. The word *shield* was applied to them by Professor Eduard Suess of Vienna in 1888, because the two best known

Fig. 324. — Stereographic map of the western hemisphere, showing North and South America, or the occidental lands, and Antarctica. After Penfield. The nuclear lands, or shields, indicated in outline: 1, Canadia; 2, Columbia; 3, Antillia; 4, Amazonia; 5, Archiplata.

examples, the Canadian and Baltic masses, have the form of a depressed shield.

There are at least eleven of these ancient land masses (see Figs. 324, 325). Three occur in North America: Canadia, Columbia, and Antillia; two in South America: Amazonia and Archiplata; two in Eurasia: Baltica and Angara; most of Africa and Australia are shields; peninsular India and Madagascar are remnants

of ancient Lemuria; while the greater part of Antarctica is ancient mountainous land, considerable parts of which rise to an altitude of about 10,000 feet above the sea.

Permanency of Continents and Ocean Basins

Older and Newer Views. — In the earlier days of Geology it was held that there was no stability in the continents and oceans

Fig. 325. — Stereographic map of the eastern hemisphere, showing Eurasia, Africa, and Oceanica, or the oriental lands, and Antarctica. After Penfield. The nuclear lands, or shields, indicated in outline: 1, Baltica; 2, Angara; 3, Ethiopia; 4 and 5, remnants of Lemuria; 6, Australia.

as such, and that there had been complete interchange between them. Even Sir Charles Lyell taught that all parts of the ocean bottoms had been land. Now, however, most geologists hold with Dana that the oceanic basins and the continents have in the main, although not in detail, been permanent features of the

lithosphere at least since the close of Proterozoic time. There is likewise much agreement among geologists in the belief that the oceanic basins are sinking areas, also spoken of as the *negative areas* of the lithosphere, because the sum of their crustal movements is downward; and in general it appears that the oceanic basins have gradually attained not only greater depth but somewhat enlarged area as well. On the other hand, the continents are the rising masses of the lithosphere in relation to sea-level, and for this reason are also called the *positive areas*, because the sum of their movements is upward (see page 228). Of these two great features of the lithosphere, the oceanic basins are the more permanent, while the continents are either locally enlarged or great masses of them are warped under or fractured and depressed beneath the oceanic level. That the internal forces of the earth have wrought great changes in the outlines of the continents and therefore in the shapes of the oceans as well will be shown in subsequent pages. In general, however, it may be said that the present oceans and continents have been more or less permanent features, and that they have been where they now are, with moderate changes in their outlines, since their origin in Proterozoic time or earlier. The greatest changes seemingly have taken place in the equatorial region and in Antarctica south of Australia and South America.

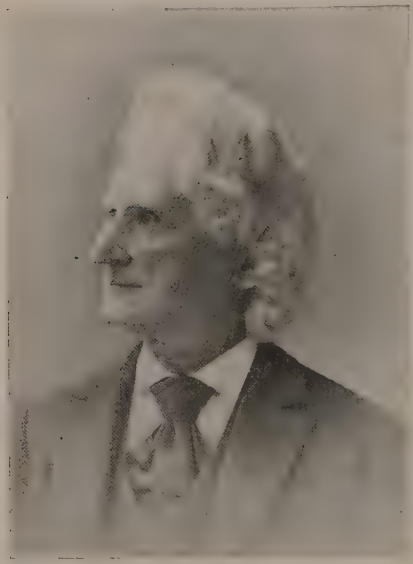


Fig. 326. — James Dwight Dana (1813–1895), at the age of eighty-two.

Proof of Permanency. — The proof that there has been no complete interchange between the continents and oceans is seen in the following facts: (1) On the continents there are almost no deposits of deep-sea origin, and the few isolated cases are met with only on the margins or on continental islands (discussed more fully in the next chapter). (2) The marine deposits on the continents are nearly always those of very shallow seas, in fact, not at all unlike those now accumulating on the continental shelves. Further proof

of this is given by the fact that the contained fossils indicate that the life was all of shallow-water types. If there had been complete interchange, on some continent there should be preserved a long and unbroken oceanic record in both the deep-sea sediments and animals, but nowhere has such a series of materials been discovered. (3) It is now established that the lithosphere is denser and therefore heavier beneath the ocean basins than under the lands, making it impossible for them to have interchanged their positions without destroying the equilibrium of the outer shell.

Deep troughs or geosynclines have, it is true, been repeatedly developed within the continents, near their margins, but even though some of these have in places subsided as much as 40,000 feet, yet at no time have they held other than very shallow seas. This is proved by the character of their sediments and the entombed fossils. Stated in another way, there has been subsidence with compensating sedimentary accumulation. This is certainly true for the Appalachian and Cordilleran geosynclines, out of which there eventually arose the Appalachian and Rocky Mountain systems. This matter will again be discussed in Chapter XXX.

Examples of Continental Fragmenting. — As the ocean basins are the more permanent features of the earth's surface and as they are the periodically sinking areas, it is to be expected that more or less large parts of the ancient continents should have been dragged beneath the waters. As an example may be cited Madagascar, a great island, 975 miles long, with an estimated area of 230,000 square miles, lying in the Indian Ocean off the east coast of Africa. No naturalist doubts its former connection with Africa, because of their similar animals, and yet the channel of Mozambique which now separates it from the mainland is from 240 to 600 miles wide, and represents a land area that has gone down to a depth ranging between 5000 and 10,000 feet. To the northeast of Madagascar lie many small islands, the Seychelles, and to the northwest occurs the Comoro group, all of which are also held to have been parts of Africa and Madagascar. Not only this, but many biologists and geologists hold that all of these lands are but parts of the comparatively recent land Lemuria.

Africa is unlike most of the continents in that it has no marginal mountain chains in the northern and central thirds, other than the Atlas Mountains along the northwestern border. The great peninsula south of the Sahara Desert consists of high plateaus ranging between 3000 and 6000 feet, and the ancient seas invaded

Africa widely only in the north and very sparingly along the east coast. The continent is a great elevated segment or block of the lithosphere with the geologic appearance of broken-down eastern and western margins. The faulted nature of its coasts is further seen in the fact that they are singularly free of large indentations and harbors. South America, on the contrary, has all along its western coast, in the high Andes, the elevated border required for a continent, but along its east coast we seek in vain for folded mountains, and it is therefore held by some of the ablest geologists that eastern Brazil has gone down into the Atlantic.

Gondwana Land. — The broken-down and submerged parts of the continents referred to above are parts of a former great transverse equatorial land, and as there will be occasion to refer to this from time to time, it is desirable to introduce the subject here, though its proper place for presentation is toward the end of the book.

Besides the facts given above, there is much other evidence of a geologic, paleontologic and zoölogic character relating to the distribution of plants and animals since the Paleozoic, tending to show that Brazil was once widely connected with northwestern Africa across what is now the deep Atlantic Ocean. This lost continent is the *Gondwana Land* (from a district of the same name in India) of Neumayr (1883) and Suess (1885) and of the zoögeographers, a vast transverse land stretching from the northern half of South America across the Atlantic to Africa and thence across the Indian Ocean to peninsular India, including Lemuria. It was in existence throughout the Paleozoic, but the Atlantic bridge and Lemuria sunk into the oceans during the Mesozoic. Gondwana when complete was comparable to another transverse land of the north, *Eria* or Holarctica, which existed when North America was continuous with Greenland and Eurasia across Iceland to the British Isles (see Figs. 436 and 488).

Kinds of Rocks Found on the Lands

The materials of the substructure of the continents and continental islands beneath the loose rocks and soil of the surface of the earth (called the *regolith*) consist of three categories of rocks: (1) the igneous, (2) the sedimentary, and (3) the metamorphosed. These various kinds of rocks composing the lithosphere have been described in detail in the first part of this book, and all that is necessary here is to recall in general terms what has been said.

Igneous Rocks. — The igneous or crystalline rocks have risen to the surface from deep within the lithosphere and have intruded themselves (intrusives) into other rocks of the same nature or into the sedimentary strata, or have flowed or been blown out over the surface as lavas and volcanic ashes (extrusives). The originally deep-seated intrusions are, however, now in many places at the surface of the earth, a condition that is due to the fact that the covering rocks, which may have been many miles in depth, have been worn away through the weathering effects of the atmosphere and biosphere. The igneous rocks are most often seen in the mountain regions of the continents and continental islands, in the oceanic volcanic islands, and especially over the shields. They are rarely met with in a flat-lying medial or basin area such as that of the United States. In a general way it may be said that the longer a land has remained above the influence of the invading seas the more likely is the prevalence of the igneous rocks. This is because of the great amount of erosion that has occurred in such places, exposing the deeper parts of the earth's crust.

Metamorphic Rocks. — The metamorphic rocks are altered igneous materials and sedimentary strata. They have been changed from their original characters, due either to great pressures which they have subsequently undergone in the areas of mountain-making, or to the proximity of igneous intrusions. Therefore the metamorphic rocks are seldom met with in areas where the lithosphere has not been deformed, but are usually seen to accompany the igneous materials. The degree of alteration is variable, and may be so complete that the metamorphic rocks simulate even in details the structures of the igneous materials.

Sedimentary Rocks. — The sedimentary strata are bedded rocks that have been laid down in sheets through the action of water and wind. The greatest quantity of stratified formations has been deposited by the seas and oceans. These are the *marine sedimentaries*, and because of the continuous wave and current action of the marine waters the materials are usually well assorted into distinctly layered and clean sandstones, mudstones (laminated shales), and more or less extensive thin- or thick-bedded organic deposits of limestones, dolomites and chalks. The nature of the marine strata will be described in the next two chapters, but in this place further consideration must be given to the deposits laid down by the fresh waters and the wind.

Continental Deposits. — The continental deposits, so named because they are always deposited on the lands by the fresh waters or the wind, instead of by seas and oceans, are formed by moving waters such as rivers (*fluviatile material*), by the more or less stagnant areas of the rivers and lakes (*lacustrine strata*), at the mouths of rivers flowing into the seas and oceans (*delta deposits*), and by the wind (*eolian deposits*). The eolian accumulations are the dune deposits of sand seen along the margins of lakes and the shores of seas, or more extensively in the arid deserts; the wind-blown dust of the deserts or of river valleys in semiarid regions is transported into moist areas, where it may accumulate as *loess*; and finally, much fragmented rocks blown from explosive volcanoes may be carried more or less widely by air currents and left as beds of volcanic ashes. The eolian deposits may be of direct accumulation from the air on the land, in lakes, and in marine waters, but more commonly are reworked and redeposited by the rains and rivers. In continental deposits alone occur also the peat and coal accumulations.

The materials of the continental deposits are rarely as well assorted and as evenly bedded over wide areas as are the marine deposits. The water-borne sands are apt to be dirty and lenticular in occurrence when of river origin, less so

in the deposits of lakes, and least of all in the deltas where the waters of the rivers are backed into shallow bays, and the material is assorted under the influence of the wind and waves. In the delta deposits there is a complete transition from the outer areas of well assorted and evenly bedded marine deposits to the inner regions of poorly assorted and heterogeneous sands and muds of the river flood plains.

Fossils of Continental Deposits. — The continental deposits are more accurately discerned by their contained fossils than by their physical characters; in them one does not find marine animals, although the organisms of the land may be carried by the streams into typical marine strata. It is usually only in the delta deposits that the plants and animals of the land and sea may be so mingled, for here the rivers carry the land organisms into the brackish water areas of the seas and even far into the pure marine waters, this being especially true for the harder woody parts of land plants. However, this transportation, if prolonged, tends to break up and destroy more and more of the land-derived organisms, and therefore the degree of perfection of such fossils in marine strata is always a more or less safe criterion as to the proximity of the land.

The more characteristic fossils of the continental deposits are in general land plants and more especially leaves; land snails and fresh-water snails and bivalves occur frequently, and less often vertebrate land animals such as mammals, reptiles, birds and insects. The animals of the dry land get into the continental deposits most often through the accident of drowning, by falling into or trying to cross bodies of water, more especially at times of great floods or forest or prairie fires. At such times thousands upon thousands have tragic endings, and many are buried in the muds and sands which are so much moved about and redeposited during floods. Entire skeletons of vertebrates may then be buried intact, and these, along with those destroyed and covered by downfalls of volcanic ashes, are, when recovered, the prizes of the natural history museums.

Life of the Land

The life of the land is very different from that of the marine waters, as should be expected because of the diverse environments; the land types live within the gaseous atmosphere and breathe it, while those of the sea are habituated to a denser, salty, liquid medium. For these reasons the fossils as a rule easily distinguish the continental deposits from those of marine origin.

Land Floras. — The floras of the dry land are markedly different and far more highly diversified than those of the seas, where

the lowly sea-weeds play an important rôle and represent the highest stage of plant structure attained. On the land alone occur the forest and fruit trees, the manifold variety of flowering plants, the palms and cycads, the grasses and cereals, the ferns, the ground-pines, and the rushes.

Land Faunas. — Dependent upon these plants are the insects in extraordinary variety, and the same is true of mammals, birds, reptiles, and amphibians. When land animals have become habituated permanently to the ocean, like the penguins among birds, the turtles among reptiles, and the whales, porpoises, and seals among mammals, their organic structures have so decidedly changed as to distinguish them easily from their land ancestors.

When we examine the life of the fresh waters, however, we quickly learn that it does not always differ strikingly from that of the sea. Many fishes of the seas annually migrate into the rivers to lay their eggs, and some have been locked up in the lakes. In the warm climates, crocodiles and alligators live along the shores of the seas, as well as in rivers and lakes. As a rule, however, the bivalve shells and snails of the fresh waters are unlike those of the present seas, while the variety of " shell fish " in the marine waters is so great as to contrast markedly with those of rivers and lakes. This is true not only for the present, but equally so far back into geologic times; earlier than the Coal Measures no fresh-water molluscs are known. The plants of the fresh waters are derived from land forms and some have adapted themselves even to brackish waters, as for instance the mangroves. Among the microscopic plants, however, there is much similarity among those found in all waters, though as a rule the special student finds no difficulty in distinguishing between those of the land and the seas.

CHAPTER XXII

OCEANS, THEIR DEPOSITS AND THEIR LIFE

The Five Oceans. — The word *ocean* is of Greek origin, and came to mean the great outward sea, the Atlantic, as distinguished from the inward sea, the Mediterranean. The word now has reference to the connected bodies of marine water that envelop the earth, of which there are five, Pacific, Antarctic, Atlantic, Indian, and Arctic. The great and deep Antarctic Ocean surrounds Antarctica, the south-polar land, connecting broadly and without boundaries with the Pacific, Indian, and Atlantic oceans; while the smallest and shallowest basin lies over the north-polar area, with limited connections into the Atlantic, and almost cut off from the Pacific by the headlands of Siberia and Alaska. The Pacific and Antarctic oceans are the largest and deepest basins and it is probable that the Pacific, the " Father of Oceans," has always been the greatest in size. The Atlantic and Indian oceans, on the other hand, although ancient, have seemingly attained their present form in very recent geologic time. The Arctic Ocean is apparently very ancient in origin, but its depth has always been shallow when compared with that of the other greater basins. (See Figs. 322–325.)

Mediterraneans. — The mediterranean seas are also to be considered as oceanic areas, since they are not only large but also very deep, though never so deep as are the deepest parts of the oceans. These seas are, in fact, parts of the oceans that are more or less widely enclosed by continents. The typical example is the Mediterranean Sea, lying between Eurasia and Africa; it is also known as the Roman mediterranean, the latter part of the name, meaning a sea in the middle of the land (*terra*), coming down to us from the ancient nations which once ruled its borders. The German name for it is Mittelmeer. Another but less typical example is the American mediterranean lying between the three Americas and walled off from the outer ocean by the Greater and Lesser Antillean islands; it includes the Caribbean Sea and the Gulf of Mexico. The Arctic Ocean is sometimes also called a mediterranean and in many ways it is such, being a deep body of marine water more or less widely surrounded by continents (see Fig. 322).

Epicontinental Seas. — The marginal or epicontinental seas (see page 82 and Fig. 69) are those shallower parts of the oceans that lie upon the margins of the continents, as for instance the Gulf of California, and more typically the row of marginal seas off the east coast of Asia, such as the China, Japan, and Okhotsk seas. The word "sea" is rightly applied to the small, shallow, salt-water bodies above indicated, but in general practice it has become synonymous with ocean (see Fig. 334).

Epeiric Seas. — Still smaller and shallower bodies of marine waters, connected with the oceans, such as Hudson Bay, Gulf of St. Lawrence, and the North Sea of Europe, have also been called marginal seas, but as they are situated wholly upon the continental platforms, they will be called in this book *epeiric seas* (see page 103). These, along with the marginal seas, will be treated in the next chapter, as they are but parts of the oceanic waters invading the continents and lie outside the ocean basins.

Nature of the Oceans

Area. — In the preceding chapter it was pointed out that 69.6 per cent of the surface of the earth is covered by water, but as the continents are more or less submerged about their edges, these marginal or epicontinental seas, at least down to 600 feet, are also truly parts of the continental platforms (Figs. 69, 88 and 334). Accordingly, the actual oceanic areas occupy 64.5 per cent of the surface of the earth. Stated in square miles, Murray places the figure "for the area of the whole ocean" at about 139,000,000. For the actual oceanic areas beyond the continental shelves it is about 129,000,000 square miles.

Arranging the areas according to depth, Murray's table is as follows:

Depth in feet	Square English miles	Percentage
0– 600	9,750,065	7.0
600– 3,000	6,964,750	5.0
3,000– 6,000	5,010,185	3.6
6,000–12,000	26,915,000	19.3
12,000–18,000	81,381,000	58.45
18,000–24,000	9,058,000	6.5
24,000–31,614	216,000	0.15
	139,295,000	100.00

Depth and Volume. — From the above we learn that most of the oceanic areas lie below 6000 feet, and that more than 65 per cent are deeper than 12,000 feet. Areas with a greater depth than

18,000 feet are called *deeps*, of which fifty-seven are now known (see page 83). The mean depth of the oceans is placed at 13,000 feet, and the volume of all the oceanic waters is said to be fifteen times greater than the mass of land protruding above sea-level. If all the deeper parts of the oceans were filled by solid material up to the estimated mean depth, it is said that there would result a universal ocean, covering the entire earth to a depth of a little less than 2 miles. These facts are recited here not only to impress the student with the immense volume of water when contrasted with the small mass of land above sea-level, but further to show, since the waters are mobile and cover nearly three-fourths of the earth's unstable surface, why it is that the oceans are enabled so readily to overflow the lands upon relatively small changes in the elevation of the crust. As the oceans are all connected one with another, a movement of the bottom of any one basin affects the oceanic level in all, raising or lowering the strand-line (see page 223) everywhere simultaneously (eustatic movements).

Original Source of Water. — In Chapter XXVI it is shown that according to the Laplacian theory of earth origin the waters of the earth were regarded as primordial and originating with the primal atmosphere. Following this view, the assumption would be that the original oceans were not only as large in volume as they are now, but even larger, for all of the water in the outer shell of the earth must have soaked into it from the oceans. This theory is no longer acceptable, for, according to the planetesimal theory, there has always been some water in the primal atmosphere, but the greater volume has been gradually added to the surface of the earth through the volcanoes and thermal springs; as Suess says, "The body of the earth has given forth its oceans." In other words, most of the oceanic water was originally water occluded or dissolved in the deep earth, and through volcanic action this *juvenile water* (steam) has been liberated and added to the already accumulated or *vadose water*.

Oceanic Level. — In general practice we speak as if there were a mean sea-level. There is, however, no such condition as a perfect spheroidal oceanic level, or a water surface equidistant throughout each circle of latitude from the center of the earth. Nevertheless, according to Murray, recent researches indicate that the differences of level at different points of the sea-surface do not depart more than 300 or 400 feet from a true spheroid of revolution. This subject is discussed further on page 221 under "datum plane."

Composition of Ocean Waters. — That the ocean waters are quite salt when contrasted with the "fresh waters" of the rivers and lakes is well known, and the subject has already been discussed on page 83 of this book. The volume of salt, when concentrated, is computed to be more than 4,800,000 cubic miles, which if spread over the United States would cover it to a depth of 1.6 miles. The salinity, however, is somewhat variable from place to place, even in the oceans proper, is markedly so along the margins of the oceans where the rivers dilute the sea-water, and is most so in shallow areas under dry climates where concentration may go on continually. The salinity, therefore, may vary from the average of 3.5 per cent and range from less than 1 to over 4 per cent. The composition of the salts is given on the page referred to above.

All of the salts and the nitrogen in the sea as well have been brought down by the rivers, as discussed on pages 43 and 151. Through the action of organisms the magnesium, lime, silica, and nitrogen are taken out of the sea-water, while the clays take up the potash, about as fast as supplied; the common salt, however, seems to have increased constantly in quantity. As the mean annual amount of salts delivered by certain streams is known (see page 151), it has been computed that the amount of sodium now in the sea could not have accumulated at the present rate in less than from 80,000,000 to 90,000,000 years.

The great volume of carbon dioxide in the ocean has been absorbed in part from the atmosphere and probably in largest amount from submarine volcanic action during long geologic time. Thus juvenile CO_2 would naturally be retained by the seas. The free oxygen so necessary for life has also been absorbed in part from the atmosphere, while the rest has come from the carbon dioxide through the action of growing plants. Both are less abundantly absorbed and retained in the warmer waters of the tropical seas.

Life Conditions. — The presence of life in the ocean is conditional upon the *law of the minimum*, that is, it is dependent upon the presence of nitrogen compounds, phosphoric acid, and silica, which are the minimal food elements, those least abundant in the sea-water. If any one is absent there can be no life, and the quantity also limits the amount of life that can exist (see page 104). As the assimilating green marine plants (see pages 409 and 482) use the minimal as well as the maximal foodstuffs and convert them into organic substance, their presence and quantity are conditioned upon the minimal elemental materials. It would seem at first that nitrogen is the first determinant, for where the quantity of its compounds is greater there also occur more assimilating plants. It appears, however, that soluble silica is of first importance, for when this element is most abundant in the North Atlantic, that is, in February, the assimilating diatoms

(microscopic algæ, Fig. 329) take their rise and upon their development follows the wonderful annual ascendancy of animal production and faunal migrations. Murray states that most of the dissolved silica yielded by the continent is tending to accumulate on the frontiers of the temperate and polar zones, especially in the Antarctic Ocean.

Ocean Currents and Temperature. — The earth rotates on its axis from west to east with a speed, in the equatorial region, of about 1000 miles per hour, while at the poles it becomes nothing. This movement, combined with the effects of the temperature differences of the zones, sets up the well-known trade winds of the tropics that blow rather strongly and constantly toward the equator and to the west, and so drag along the warm tropical surface waters. These in turn impinge on the eastern sides of the continents and are then variously deflected, in the main according to the shapes of the lands, causing great streams of heated water, or oceanic currents, to flow toward the poles as previously described, page 85 and Fig. 70. In this way the currents assist not only to equalize the temperature and salinity of the sea water, but also to warm the air in the higher latitudes and to spread the life of the oceans. At the same time the polar waters, receiving but little solar heat and cooled by their great fields of ice, flow equatorward, and, since they are heavier than the warm tropical waters, sink beneath them into the depths of the oceanic basins. Therefore, in all of the depths of the ocean below about 4000 feet the temperature is very low and fairly uniform, near the freezing point of the Fahrenheit scale (35° to 32°, and in the deeper abysses 31°). At the surface the temperature varies from about 80° at 5° north latitude (the warmest area) to about 32° at the poles.

Besides the great ocean currents there are many others of varying intensity set up by differences in temperature of the air and water, differences in the pressure of air and water, and varying degrees of salinity, and still others caused by the winds, the waves, and tidal action. At the surface, the Florida current of the Gulf Stream at its narrowest place has a mean annual flow of 3 miles per hour, but during the warmest and coldest months this rises to 120 sea miles per day. East of New York the rate of flow is about 48 miles per day, and it becomes less and less farther northeastward. From this rapid and exceptional streaming, the rate of flow or *ocean drift* ranges down to zero. In depth the surface currents penetrate very variably, and in general the stronger currents are near the lands along the continental slopes, oceanic

islands, and submerged ridges. As a rule, the penetration is less than 1000 feet, but in the Azores strong currents still exist at 2600 feet. In the tide-swept straits between the Canary Islands moving currents are present at 12,000 feet, and off the continental slope of Ireland they occur at 6000 feet. Therefore the ocean currents sweep the higher swells and ridges of the bottom clean of ooze, and level the bottoms into monotonous, undulating, abyssal plains.

Halistases. — In Fig. 70 are illustrated the oceanic currents and the streamless intermediate areas, one of which is known as the Sargasso Sea. Sargasso, a seaweed common to the West Indian waters, is torn from the bottom by storms and distributed by ocean currents. Much of it drifts into the North Atlantic eddy, where it continues to live for a time, and where grows a rich plankton of microscopic plants. Here also occurs an abundance of specialized or widely distributed and hardy animals — a nomadic fauna (55 species) of small molluscs, pteropods, bryozoans, barnacles, fishes, and crabs. Of such streamless regions there are six known, and they form the *halistases*, or standing seas, of Haeckel.

Light Penetration. — Since it is the green plants which assimilate inorganic matter into their living substance, and since animals depend on plants for their subsistence, it becomes necessary to know to what depths the sun's kinetic energy penetrates into the oceans. Verrill relates that he has dredged red algæ two inches tall attached to boulders at a depth of 480 feet off Eastport, Maine. White objects can be seen in the clear tropical waters with the unassisted eye down to 200 feet, and coral reefs to 145 feet. Here the sun's rays enter nearly vertically, but toward the poles the angle is ever more slanting. Therefore, the vertical penetration is much less away from the equator, and at 67° north latitude the bottom can be seen in clear water only down to 80 feet. However, through the aid of photographic plates, it is now established that considerable quantities of light in the tropical regions go down to 3250 feet, though this is true of only the ultra-violet and blue rays. Even at 1625 feet no red and green rays have been noted, but at 325 feet all of the rays of ordinary bright sunshine are present, though red light is the least strong. The importance of this matter is that the conversion of carbonic acid into plant structure does not go on under the kinetic action of the blue and violet rays, but such assimilation is active under the red, orange, and yellow rays. From this we see that assimilating plant life is practically restricted to the upper 500 feet of the oceanic waters. The portion of the ocean penetrated by sunlight is, therefore, spoken of as the *diaphanous region*, or the zone of transparency, and the dark region, where plants do not live, is known as the *aphotic region*, or the zone where sunlight is absent.

Physical Regions of the Oceans

Areas of Shallow Water. — As the strand, the littoral, and the deeper continental shelf are within 600 feet of depth and properly belong to the continents, they will be discussed in the next chapter.

Continental Edge and Slope. — In general, at the depth of 600 feet occurs the *continental edge*, and beyond this there is a comparatively rapid descent into the oceanic basins, as described on page 105.

The reason why there are continental shelves, and why these terminate at a depth of 600 feet in most places, is because it is at this depth that the ocean storm waves cease to act on the bottoms of the seas. The areas of the continental shelves are, therefore, the regions of agitated waters bordering the lands and capable of holding mud in suspension to depths of not over 600 feet (see Fig. 334). The mud-mantled slopes of the ocean basins mark the slow settling of the mud from the waters beyond the reach of wave agitation. Consequently, in all ages the continental shelves must have been constructed at this depth facing the open oceans. The slope is not steep, however, when compared to the hillsides of the lands. In general, it is long and smooth, with a grade ranging from one foot in ten to one foot in thirty, but extending to a depth of one, two, or three miles. This slope is known as the *continental slope*, and occupies from 8 to about 25 per cent of the ocean areas. Only 5 per cent of the ocean occurs between the depths of 600 and 3000 feet, and about 3.6 per cent between 3000 and 6000 feet (see table, page 471). Below this point the descent is less rapid, for 19.3 per cent of the ocean lies between 6000 and 12,000 feet. Beyond this are the submerged plains with their swells, ridges, and peaks, making up about 65 per cent of the oceanic areas. Within the ocean plains also occur the *deeps*, but their combined areas make up less than 7 per cent of the entire ocean basins.

Regions of Oceanic Muds and Oozes. — The continental edge is also the *mud-line*, for everywhere over the ocean bottoms only fine-grained mud is being deposited; on the continental slopes, green and blue muds, coral mud, and volcanic ash of coarser grain (see page 105 and Fig. 327); and elsewhere, green, blue and red muds of the finest grain. The mud of the continental slopes is mostly derived from the continents and is carried seaward by the action of the waves and the currents; while the impalpably fine muds of the oceanic abysses are very largely of organic origin and mainly result from the microscopic floating forms of plants and animals that

Fig. 327. — Distribution of oceanic oozes, on Mercator's projection. *Dotted*, areas of terrigenous deposits; *vertical ruling*, areas of Globigerina ooze and coral muds; *horizontal ruling*, areas of red muds; *horizontal broken lines*, areas of Diatom ooze. After Murray and Renard, modified from Kayser's *Allgemeine Geologie*.

live in the upper sunlit waters, and upon their death rain into the deeps, where their soft parts are food for the life of the bottom, and their skeletons go to make up the muds of the deep seas. Wind-borne volcanic and desert dust and the disintegrated floating pumice are also contributed, however, and become notable in the composition of the red clays which floor the deepest parts of the ocean basins.

The coarse and very variable deposits of the continental shelves occupy only about 9 per cent of the oceanic areas, 15.5 per cent is covered with the fine blue muds of continental and organic origin (known as the *hemipelagic deposits*), while 75.5 per cent consists of oozes, mainly of organic origin (*pelagic deposits*). As the sediments of the shelf seas and of the continental slopes, occupying together about 25 per cent, are so largely derived from the adjacent lands, they are also spoken of as the *terrigenous deposits* (Fig. 327).

Blue and Green Muds. — In any classification it is difficult to draw sharp lines, and though the great mass of blue muds is laid down beyond the continental edge and mainly on the continental slopes, still they are also found on the continental shelves in the quieter water of less than 600 feet depth. This fine mud

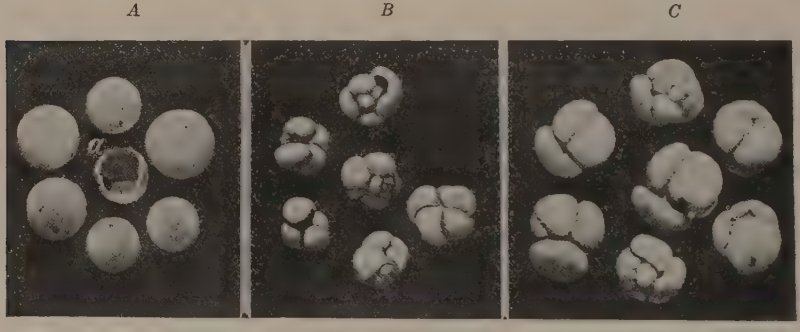


Fig. 328. — Three species of Foraminifera washed out of Globigerina ooze. × 12. *A*, *Orbulina; B* and *C*, *Globigerina.* After Flint.

is brought to the seas by the rivers, but only the finest of it is held in suspension long enough to carry it beyond the average depth of wave action at the continental edge. It owes its blue color to the fact that the iron of the mud is united with organic matter, but where the mud has been oxidized and the organic matter removed the mud takes on a red color, such as is seen in the Yellow Sea off Asia and certain areas off the coast of Brazil and western Africa. In the main, however, the hemipelagic muds are blue in color, and they shade seaward into the oceanic oozes. *Green mud* is only a variety of blue mud and derives its color from the presence of grains of glauconite (a silicate of alumina, iron, and potash, with water). These muds are found on the continental slopes near bold coasts and where currents from different sources alternate with the season, as off the Atlantic coast of the United States.

Volcanic muds, the ashes of volcanoes, are found at nearly all depths, because volcanoes are situated not only along the borders of the continents but also in various parts of the oceans. The ashes blown high in the air are transported far and wide. They dominate the nature of the deposits, however, chiefly in the deepest parts of the oceans, because there all the calcareous débris from the animal world is dissolved as fast as it originates, leaving a scanty insoluble residue.

Globigerina Ooze. — Globigerina ooze is a fine organic mud with more than 30 per cent of calcium carbonate, derived in the main from the tests of the microscopic animals known as Foraminifera, of which *Globigerina* and *Orbulina* are the most prevalent forms (Fig. 328). These animals, of which there are about twenty kinds in tropical regions, live in the sunlit waters and after their death drop into the abyss. To them in the warmest waters are added other micro-

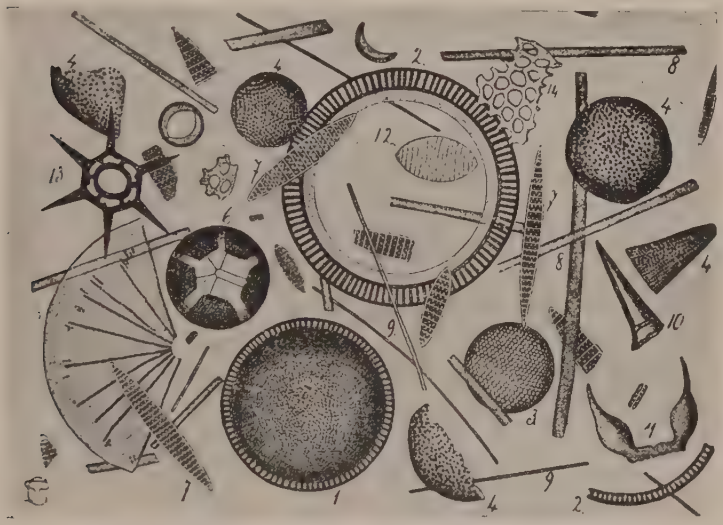


Fig. 329. — Many species of Diatoms washed out of Antarctic Diatom ooze. × 300. From Krümmel's *Oceanographie.*

scopic calcareous particles derived from lime-secreting algæ (coccospheres and rhabdospheres, Fig. 332). This type of ooze is more widely distributed than any other, and usually occurs in depths of less than 15,000 feet and more than 6000 feet, although around tropical oceanic islands it may form in the shallowest of seas. On the one side the Globigerina ooze merges into the blue muds and on the other into the red clay, for at greater depths than 15,000 feet the solvent powers of the abyssal waters, as previously stated, dissolve the lime and carry it away in solution. The Globigerina oozes originate in the warmer waters and occupy nearly 30 per cent of the ocean bottoms (Fig. 327).

Diatom Ooze. — In the surface waters of the oceans also live microscopic plants that secrete beautifully ornamented siliceous tests, and of these a single species is particularly abundant in the polar waters (Fig. 329). Their tests after death

fall into the deeps and there form the Diatom ooze, which occupies about 6.5 per cent of the oceans in high latitudes (Fig. 327). See also page 107.

Radiolarian Ooze. — The Radiolaria are microscopic animals that also secrete very beautifully shaped and ornate tests of silica; while they occur in all oceans they are most abundant and varied in the tropical regions of the Pacific and Indian oceans (Fig. 330). The area of these oozes is small, being about 3.4 per cent of the oceans. Murray states that the Radiolarian ooze may be regarded as a variety of red clay containing many radiolarian skeletons (Fig. 327).

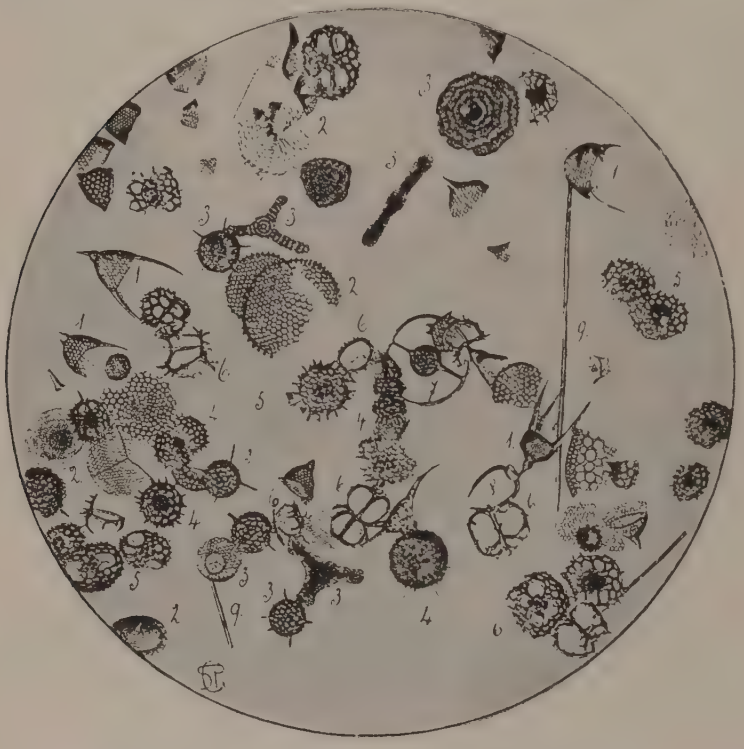


Fig. 330. — Many species of Radiolaria washed out of Radiolarian ooze. × 60. After Krümmel.

Red Clay. — Red clay is usually found in depths greater than 16,000 feet and is the most widely distributed of the oceanic deposits, occupying about 36 per cent of the oceans (Fig. 327). The red color is due to oxide of iron. The clay, Murray tells us, is in the main a hydrated silicate of alumina, derived principally from the decomposition and disintegration of pumice and other volcanic products long exposed to the action of sea water. In the greatest depths there is no calcium carbonate present, but in the lesser depths the clay shades over into the Globigerina ooze, and there may be as much as 30 per cent of it in the clay. On the other hand, the red clay merges into the Radiolarian ooze. The rate of formation of red clay is exceedingly slow. In it have been detected grains of meteoric dust.

Age of the Oceans

Lack of Abyssal Deposits on the Continents. — Geologists have long sought on the continents for geologic sediments comparable to those now forming in the great abysses of the ocean, but to no avail. The German geologist Walther, who has carefully examined recent abyssal sediments, in his geologic studies has considered repeatedly whether any fossil rock possesses abyssal characteristics, and nowhere has he met with strata, either of Paleozoic or Mesozoic age, that by their structure and nature of deposition correspond to the present sediments of the oceans. Sir John Murray also failed to find oceanic rocks. However, a microscopic and chemical analysis of certain deposits on islands such as Barbados and Trinidad of the American mediterranean, Sicily and Malta, and possibly Haiti, Jamaica and Cuba, shows that oceanic deposits of Tertiary age occur on them. Chamberlin says: "The cases in which true abysmal deposits now appear above the sea-level do not, when all are put together, appear to attain in area so much as one per cent of the total earth surface. Moreover, nearly all of these oceanic deposits lie in the zones of exceptional crustal instability." This evidence is, accordingly, in harmony with the theory that the oceanic areas have in the main always been oceans, or, in other words, that the oceans are permanent features of the earth's surface.

Modern Origin of Abyssal Animals. — In the abysses there is not a trace of Paleozoic life, though from twenty-five to thirty-five genera, with a larger number of species, are known in the present shallow seas. Again, an analysis of the present abyssal animals reveals no ancestors older than the Triassic, and most of them date from the Jurassic and Cretaceous. Walther concludes from this evidence that the present deep oceanic fauna migrated from the shallow waters during Mesozoic time, and that "the peopling of the deep sea can be traced at the earliest to the Triassic."

While this evidence is correct, it does not necessarily follow that the oceans have all become abysmal since the close of the Paleozoic. While the juvenile water added to the oceans since that era has been considerable, yet it may not exceed 10 per cent; we see, accordingly, that these basins must have been long previously nearly as capacious as they now are to hold the vadose waters. Moreover, we must not forget that Gondwana was broken through by the Atlantic toward the close of the Mesozoic, and Eria during the Tertiary — areas that have taken up great quantities of water and thus brought about a general reduction (eustatic) of the sea-level. It is this geologically recent fragmenting of the continents that has resulted in the present high average level of the lands above the strand-line.

Life of the Marine Waters

Plankton. — The life feature of prime importance in the ocean is the *plankton*, a term that Haeckel proposed for the passively floating life of the sea, which is also a part of the *pelagic life*. The great majority of the plankton is made up of primitive plants (mainly algæ, Figs. 329, 331 and 332) and animals (mainly Foraminifera and Radiolaria, Figs. 328 and 330, and, at certain seasons, the larvæ of higher animals) that are microscopic in size. It has been variously described as " a wealth of life more abundant than is contained in the richest and most luxuriant forest," " the drifting fauna and flora of the sea," and " the pastures of the sea "

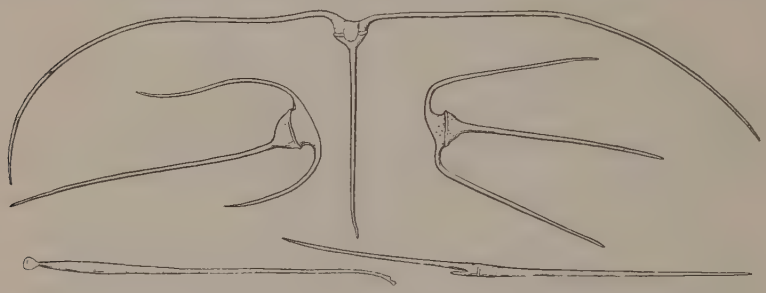


Fig. 331. — Three species of pelagic algæ (Peridinians). Greatly magnified. From Chun's *Tiefen des Weltmeeres*.

as compared with " the grass of the fields." The quantity and variety change from place to place and with the season of the year, being far more abundant close to the lands and in temperate waters than out in the open ocean and in polar seas. Of microscopic unicelled plants alone there are in the densely populated region of the northern Atlantic from 3000 to 12,000 individuals in a quart of water, though ordinarily there are not more than 300. The plankton lives and propagates mainly in the upper 300 feet of the seas, though in greatly diminished quantity it exists down to 1100 feet, where no more is found. It is the cause of most of the phosphorescence seen glowing at night, for much of it then rises to the surface. On hot, sunny days it floats at from 30 to 160 feet beneath the surface.

The plankton is the food for most of the animals living on the bottom of the oceans, which are collectively known as the *benthos*, and all animals that swim freely about are dependent for sustenance upon it. In other words, the plankton is the ultimate source

of food for all marine animals. The planktonic plants, when growing, take in carbonic acid and free the oxygen, bringing about more favorable habitats for animals, a condition attained in greatest measure in temperate waters.

Life of Shelf Seas and Continental Slopes. — The realm of greatest abundance and variety of life is in the shelf or epicontinental seas bordering the continents, and while the largest quan-

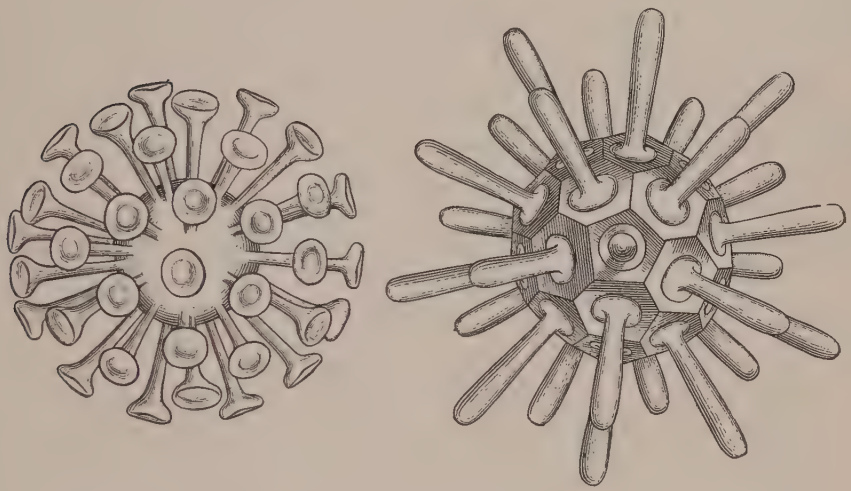


Fig. 332. — Two species of Rhabdospheres, lime-secreting algæ. × 2200. From surface of Atlantic Ocean. Challenger Expedition Reports.

tity is in the temperate waters, the greatest number of kinds occurs in the warmer waters. Bottom-living plants, the seaweeds, are most prolific in waters down to about 400 feet, and none are known beyond 600 feet. This is the most striking difference between the life of the shallower waters and that of the oceans proper, for the animals of the deeper parts of the shelf seas continue down the continental slopes, and, even though in reduced quantity, they are still comparatively varied and abundant at depths of 9000 feet. Beyond this they diminish quickly and over the abyssal plains they are very scarce indeed, consisting only of forms highly modified to cope with the peculiarities of their environment.

Kinds of Abyssal Animals. — Sir John Murray in the famous *Challenger Reports* presents a summary of all the abyssal animals

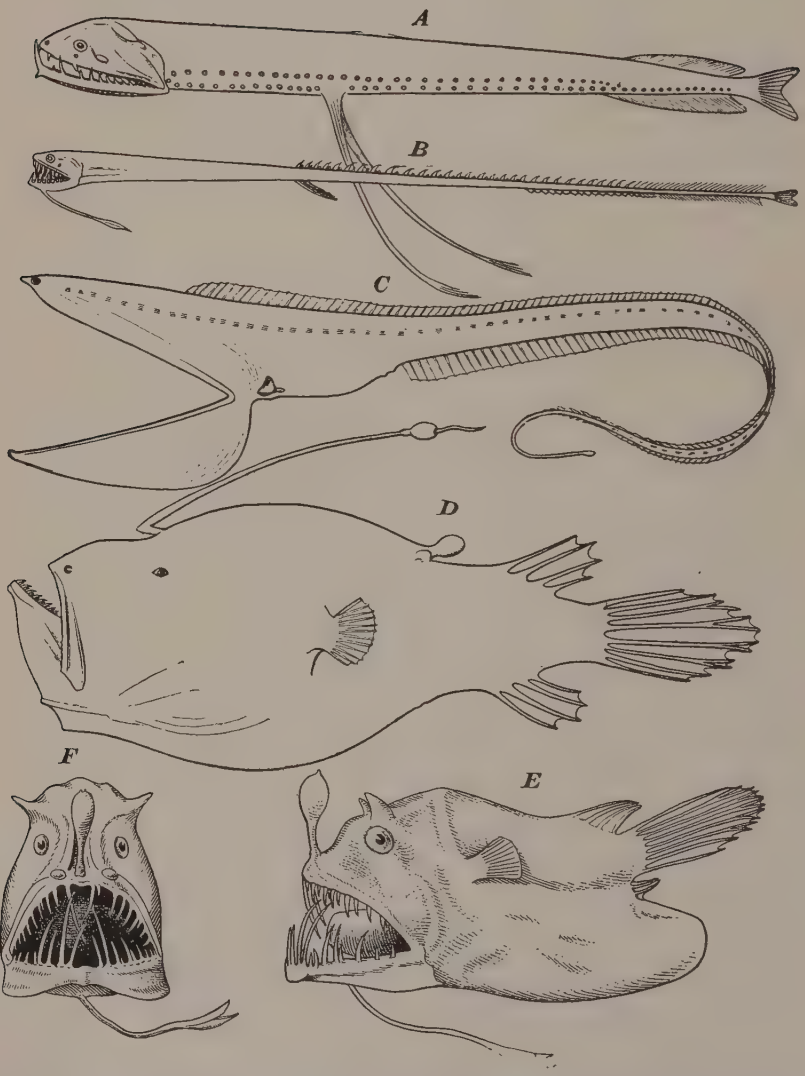


Fig. 333. — Five species of small, black, deep-sea fishes. After Goode and Bean, *Oceanic Ichthyology*. *A*, *Photostomias guernei* (length 1.5 inches, taken at 3500 feet); *B*, *Idiacanthus ferox* (8 inches, 16,500 feet); *C*, *Gastrostomus bairdii* (18 inches, 2300–8800 feet); *D*, *Cryptopsaras couesii* (2.25 inches, 10,000 feet); *E*, *F*, *Linophryne lucifer* (2 inches).

known up to that time (1895), and his figures have not been much modified since. They are as follows:

At	650	feet,	more than	5000	kinds	of	bottom	animals	live
"	6,500	"	about	600	"	"	"	"	"
"	13,000	"	"	400	"	"	"	"	"
"	16,250	"	"	150	"	"	"	"	"

Previous to 1910, only thirty-five specimens of abyssal or bottom fishes had been taken, representing twenty-one species. This scarcity of specimens is equally true among the bivalves, brachiopods, bryozoans, crinids, starfishes, hydroids, actinians, and corals, the most abundant animals being the sea-cucumbers, ophiurids, and sponges. Finally, on the red clays there is almost no life, other than a few worms, because of the great scarcity of food. In general, it may be said that the abyssal life is small, frail, and devoid of thick and strong skeletons. (Hjört.)

Phosphorescence of Oceanic Life. — The waters at the bottom over the abyssal plains are everywhere dark, icy cold, and almost without movement. In addition, the pressure is great, and as there are no barriers the highly specialized animal life, in the main invertebrates, has migrated quite uniformly over them. The sparse fauna consists mostly of blind forms, and where eyes have been inherited and are still functional, as in some fishes, they are enlarged to great size that they may catch any ray of light, for nearly all abyssal invertebrates are phosphorescent, thus being able to " transform the dark depths into a magic garden."

Intermediate Abyssal Fishes. — There is another realm for abyssal fishes, but this lies far above the bottom of the oceans, between 480 and 4800 feet, with the greatest abundance at about 1000 feet beneath the surface. About 1000 species have been described from this zone, and they are now known to be of more or less localized forms, living at lower levels during the day and at higher ones at night. At the lowest level these fishes are apt to be black or red, colors invisible at this depth because of the absence of red light, and some have telescopic eyes adapted to make use of the blue and violet rays of sunlight. The abyssal fishes are small, black, strange-looking animals, their large heads nearly all mouth and teeth, with long sensory tentacles or feelers and " torches " with phosphorescent tips, and an abundance of glowing spots distributed in lines over their sides. " The higher we ascend towards the surface of the sea," says Hjört, " the more varied become the forms and colors of the organisms, and the more diversified become, also, their conditions of life." (See Fig. 333.)

CHAPTER XXIII

SEAS, THEIR NATURE AND DEPOSITS

In the previous chapters we saw that the oceans are more than full, and that they have spread over the continents to the extent of about 600 feet in depth, developing the shelf or marginal seas and the epeiric seas. It should, however, be added that the continental shelf is known to have depressions in it as deep as 1600 feet, though such is very rarely the case.

Definition of Seas. — In general use the word *sea* is interchangeable with ocean, but in Geology it is more often used in a restricted sense and in its original meaning. It appears to have originated with the peoples of northwestern Europe who were familiar with the North Sea and the East or Baltic Sea. These are bodies of marine water that in the main are under 200 feet in depth, and lie upon or within the continent; hence they contrast distinctly with the far deeper and larger mediterraneans and the abyssal oceans (Fig. 334). The marginal or shelf seas are also known as *epicontinental seas* because they lie upon the borders of the continental platforms (see page 82 and Fig. 69), and the Germans often call them " flat seas " because of their shallowness and their flat bottoms.

The seas of the continental shelves are not only the regions of greatest abundance of marine life, as previously stated, but also the ones from which all the other water bodies of the world have been colonized. Thence, bottom-living forms and swimming organisms have made their way into the abysses and others have voluntarily or involuntarily attained to a life in the inland lakes and rivers through modification of their habitats from salt to fresh waters, or, by changing water-breathing organs into lungs, have even become denizens of the dry land itself.

Epeiric Seas. — In the geologic past all of the continents have been more or less widely flooded by overlaps of the oceans, all of which are thought to have been shallow and usually under 600 feet in depth, though in places they undoubtedly were deeper. Long ago Dana called these *continental interior seas* or *interior seas*, and his terms should have prevailed, but unfortunately the name " continental deposits " came to be applied later, not to the sediments of

Fig. 334. — Lands (white), seas (dotted), and oceans (white). The areas of the shelf (epicontinental) and epeiric seas are shaded in dots, and the largest relic seas are in solid black.

the shallow marine waters but to those of the fresh waters. As the term " continental deposits " in this sense is now ingrained in Geology, we can no longer use Dana's " continental seas," without raising a question in the mind as to what is meant when their deposits are considered. For this reason we propose here to use *epeiric seas* (meaning seas that lie upon the continents) for the bodies of water that lie within the continents in the downwarps of the continental masses. These areas in times past have experienced great changes through variations of sea-level, sometimes being more or less completely emptied of their water, or filled with sediments and turned into land. Examples of present epeiric seas are Hudson Bay, the Gulf of St. Lawrence, and the Baltic Sea (Fig. 334).

Extent of Seas. — At present the shelf and epeiric seas occupy about 5.1 per cent of the earth's surface, or nearly 10,000,000 square miles, but in the past they were vastly greater, for the North American continent has several times been flooded by epeiric seas that covered from one third to about one half its areal extent. In fact, almost all of Stratigraphic Geology is a study of the sediments of epeiric seas (marine deposits), of fresh waters and of the atmosphere (continental deposits), while it deals little with those of the shelf or epicontinental seas and scarcely at all with the ocean oozes.

Nature of Seas. — The seas are wholly transparent to the sunlight (diaphanous); accordingly, they constitute the only marine area where the bottoms are more or less covered with ground-dwelling plants, and all animals that feed upon such plants are restricted to these waters. As the seas are adjacent to the lands, receive the rivers, and feel the full effect of the waves and tides, it is natural that they should vary greatly in temperature, salinity, agitation of the water, and sedimentation. Since the oceans are mobile, any movement within the earth's mass is reflected by them and causes the seas to become shallower or deeper, or even to be transformed into dry land. Because of these constant changes in the physical, chemical, and organic environment, the epeiric and shelf seas are also the scene of severe struggles among their inhabitants and consequently are the principal arenas of marine biotic evolution. We may then say that the degree of intensity of all these interactions is most marked toward the land and diminishes away from it down the continental slopes.

Effect of Rivers on Sea-life. — Rivers enter the sea through estuaries or deltas, and here the environment of the rivers meets

that of the seas, blotting out most of the marine organisms, and not only piling up the greatest depths of sediments, but also bringing about the most marked variations in sedimentation. Very little of marine life has ever been able to withstand the environment of rivers and so accommodate or permanently adapt itself to fresh water.

Divisions of the Seas

On the basis of their depth and their rock character, we may divide the seas into the strand, the shallow-water littoral, and the deep-water pelitic areas.

The Strand. — All students of the seas are agreed that the strand (the shore or beach) is the most easily defined region, since it lies between high and low tides. In most places the strand is a narrow one, varying in width up to several hundred feet, but where the bordering lands are very flat it may attain to a width of miles. Here the deposits are exceedingly variable in composition and usually coarse in grain, for it is naturally the region of most active wave force. Along the strand we may meet with cliffs, or rivers may bring in gravels, and from either source are formed conglomerates and coarse sands. Conglomerates, as a rule, are of continental origin, but those of the seas either occur at the base of formations, where they are made by waves beating against the cliffs, or are the interbedded gravel deposits brought by the rivers. Where the sea shades into the land may occur the finer sands or muds, which are often rippled, sun-cracked (Fig. 416), or trampled over by the land animals, thus preserving their tracks (Fig. 420). It is very important to bear in mind that sun-cracking is practically restricted to the deposits of the strand and to continental formations (see page 269), for these are the sediments that in the main are exposed to the air sufficiently long to be dried enough to bring about shrinking and tensional cracking. However, there are also areas of the strand, as in the present Runn of Cutch, India (8000 square miles), where marine *playas* (broad mud flats) are bared for months at a time from the sea. It is very probable that the sun-cracked Paleozoic water-limestones of the Appalachian region were formed in this way.

The nature of the strand deposits is, however, dependent not only upon the topography of the land and the proximity of the rivers, but equally upon the climate and the waves and currents that are produced by the winds and tides. The winds constantly vary in intensity and shift in direction, and with them the waves

and currents, bringing about, in the "sea mills" thus formed, a reduction in size of grain, an assorting of rock according to mass and specific gravity, and a drift of material now in this direction and now in another. However, the materials of the strand are usually not in thick deposits and the marine conglomerates are as a rule under 10 feet, though they may attain locally to 100 feet.

Life of the Strand. — The strand is also the *amphibious region*, for sometimes it is a part of the dry land and again it is under the sea. For this reason its life is a peculiar one, highly adapted to an environment that is neither wholly of the one nor the other region; nevertheless most of the organisms are of the sea. When the tide is out they do not feed and most of them are buried in the wet ground, hidden beneath the rocks, under the seaweeds, or in pools of water. The kinds of animals that are actually restricted to the strand are not many, for most of its dwellers are forms that also live in the adjacent region of permanent water.

Littoral Seas. — Below the strand is the *littoral region*. Some use this term in place of strand, and still others include in it the entire depth of the seas. The Latin word, *litoralis*, means *belonging to the seashore*, and in this book we shall so use it, but continue the region from the lower limit of the strand to a depth of 150 feet, the latter point being chosen because at this depth *most* of the assorting power of the waves and their undertow ceases. The littoral region therefore merges landward into the strand and seaward into the deeper waters or pelitic seas. The waves of these shallow waters are most powerful and push the coarser material landward, piling it up toward the strand, while the finer substance is dragged seaward. The sediments, like those of the strand, are exceedingly variable, running from conglomerates to clean, coarse, shifting sands, dirty sands that consolidate and do not shift, and coarser muds. The offshore portions of delta deposits are also laid down in these depths and their shifting sands are dominantly rippled and occasionally cross-bedded. These littoral deposits, due in the main to the inflowing of the rivers, are apt to have remains of land animals and more especially of land plants, such as leaves, stems, and wood, objects far less prevalent in the deeper water deposits. It should, however, be said that but little vegetable matter is entombed in the deposits of the warm littoral waters of the tropics, for the great drifts of timber can only be preserved in temperate and colder waters.

As the storm waves act with some force to depths of about 150 feet, we see again why the littoral region is marked by conglom-

erates, by sands that are rippled, and often more or less cross-bedded, and by quick alternations of sands and muds, both vertically and horizontally; in a word, it is more than any other the region of heterogeneous deposits. Ripple-marks have been seen and measured in depths of 75 feet with the ridges still 3 inches apart, and fine sand has been thrown on the decks of ships where the waters were 150 feet deep. Therefore, great storm waves can lift and rework the littoral bottoms, break up the muds into tabular fragments or roll them into mud-balls, and in this way make the well-known *intraformational conglomerates*, so called because the fragments of which they consist are of the same deposit and age as the rocks in which they lie, and are not of foreign rocks, as is the case with the ordinary type of conglomerates.

The littoral region is also marked by *banks*, those flat shallow-water areas far out from land, such as form the great fishing ground to the south of Newfoundland and to the east of the Maritime Provinces of Canada. These banks are due in the main to currents that have piled up sand and muds; it is, however, not only the currents that do this work, for, as explained on page 40, sea-water rapidly precipitates the muds brought into the sea by the rivers. Thus all the coarser terrigenous material is dropped in the littoral, and only the finest particles are carried by the lessened currents into deeper waters.

To the tropical waters of the littoral region are restricted the great coral reefs, and consequently, with the assistance of the lime-secreting seaweeds and the denitrifying bacteria, these and the adjacent deeper waters are the areas of greatest limestone making. Here also in the shallow waters are formed the calcareous oölite deposits. In the temperate and cooler waters the reef corals are absent, and even though calcareous algæ are present they are of other kinds which are far less effective as makers of limestone. In the same waters but in depths between 35 and 90 feet are found those green seaweeds with wide and fluted blades that are yards in length, known as Laminaria. Growing in great tangles they form miniature forests and are characteristic of the *Laminarian zone*.

It is a well-known fact that *pure sandstones are poor in fossils*, but, when mixed with clay and more especially when limy, do contain them, sometimes in considerable abundance. This is because clean sands are laid down well within the zone of wave agitation, which not only washes out the mud and carries it farther oceanward, but also shifts the sand. Such places have no seaweeds living on

the bottom, and are generally unfavorable habitats for life because of the shifting nature of the deposits and the grinding action of the sharp sands on the organisms. Further, the porous sands permit circulation and solution and have no diffused lime to protect the shells from such dissolving action. It is, therefore, in limy sediments that fossils are most abundant. The subject is referred to again later in this chapter (under diagenesis).

Deep-water Pelitic Seas. — Beyond the littoral seas are the deep-water pelitic seas, which include all the waters of the continental shelves and the epeiric seas from about 150 to 600 feet. The word *pelite* is much used in the study of rocks (Petrology), and in the main refers to fine-grained mud rocks; in connection with the seas the word, therefore, is intended to have reference to the widely uniform and fine-grained character of the deposits of these deeper seas. To these depths the storm waves generated at the surface rarely reach, sufficing only to stir the fine mud which is carried thus far from land, but in most places there is some movement of the waters due to the tidal and oceanic currents. Here also the green seaweeds become less and less abundant with depth, while the brown and red algæ are generally the forms of the deeper waters. On protected coasts, however, the continental slope into the oceans begins at 300 to 400 feet of depth, owing to the lessened wave action.

The deposits of the pelitic seas are the well assorted and widely spread fine sands, and the sandy, clayey, and calcareous muds, along with greater accumulations of organic débris. It should, however, be understood by the student that sedimentation in the deep-water seas is dependent not only upon their currents, but also upon the height of the adjacent lands and the nature of their climate (whether warm or cold, dry or moist), upon whether the rocks are soft strata or hard crystallines, and upon whether the land is clothed with vegetation or is a desert. These general tendencies are further altered by the currents, so that locally even the pelitic seas have deposits that are characteristic of the littoral seas.

Origin of Concretions in Pelitic Seas. — Where cold and warm water currents impinge on one another they are shifted from time to time by strong winds, and in such regions it occasionally happens that the cold shore waters are blown far into the areas of the deep-water seas, killing off many of the warm-water animals. Such an area occurs off the New England States, where in 1882 almost all of the fishes and other swimming animals were killed. The carcasses eventually fall to the bottom and form nuclei which

in their decomposition set up the formation of concretions that are often phosphatic. Similar beds of concretions are also met with in the ancient deposits.

Relic Seas and Lakes. — Peschel in 1883 directed attention to the great bodies of fresh, brackish, or even highly saline waters now completely cut off from the mediterraneans and oceans, but whose present life shows clearly that they were once in open connection with them. The best-known examples of these severed bodies of marine waters are the Black Sea and the Caspian Sea, both of which were once widely connected with the Roman mediterranean (Fig. 334). These seas are therefore marine relics of the past that have gradually been freshened through the inflow of rivers. In the same way we speak of *relic faunas* or *relic species*, meaning that they are relics which have adapted themselves to their present fresh-water or brackish-water habitats, the relic seas (see pages 73 and 79).

The Caspian Sea is the largest land-locked body of water, with an areal extent of 170,000 square miles. Its surface lies about 83 feet below sea-level, and in the north it is very shallow, though in the south it attains to a depth of 3190 feet. It has now no outlet and its waters are removed by evaporation as fast as they are received. Formerly it was a vast inland mediterranean with epeiric connections extending to the Arctic Ocean and the Roman mediterranean. The fauna is a deficient one, but the fishes are so abundant that the fisheries are the equal of those of the northern Atlantic Ocean. Sturgeon are exceedingly common, and the Caspian is also the source of the famous Russian caviar and of isinglass. Other marine animals found in this sea are salmon, herring, porpoises, and seals.

American examples of relic seas and lakes are Lake Ontario and more especially Lake Champlain. Squids are still present, though rare, in Lake Onondaga, once a tributary of Lake Ontario, while the best demonstration that Lake Champlain is a relic sea is seen in its elevated beach deposits of very recent origin (Pleistocene), which have an abundance of marine shells and the bones of seals and whales.

Stagnant Sea Areas. — In the shallow parts of the oceans and in all seas there are large and small areas where the waters are stagnant, and because of the lack of currents the animals living on the bottom, the benthos, soon consume all of the free oxygen that has been absorbed in the main from the atmosphere. Such bottom waters are said to be "stale," and they are taken possession of by sulphur-making bacteria which feed upon the micro-organisms and other life

that falls from the sun-lit, oxygen-absorbing surface zone. As the result of the bacterial life processes, the bottom waters become more and more foul through the liberation of sulphuretted hydrogen gas.

On the other hand, where the prevailing winds are strong toward the land, there is developed a marked seaward undertow that sweeps the bottom clean of deposits and of the organic products of decomposition from the abundant life of the littoral seas. The material gathers in the currentless depressions of the pelitic seas, where it accumulates as black mud. Such *dead grounds* are known in many seas. Others, such as the submarine channel of the Hudson River, are known as *mud holes*. The abundance of organic matter colors the muds blue-black to black and they abound in petroleum and in sulphide metals, usually iron pyrite. Many formations of this kind are known in Geology, and some of them have a petroleum content as high as 20 per cent.

Walther says that as long as a part of the seas is in open circulation with the ocean and its waters are constantly interchanged and the normal salinity maintained, there will live and be continued a normal marine fauna. As soon, however, as the free circulation of the water ceases, as in a quiet bay or between islands of an archipelago, all normal conditions are altered. Such stagnant places are characterized by accumulations of organic matter, by the development of poisonous sulphuretted hydrogen gas in the water, and by the vanishing of bottom-living organisms. Only the floating and swimming organisms or drifted plant material attain these quiet places, where they are often wonderfully conserved in the muds. This detailed preservation is well known in America, for in the black shales at Banff, Canada, and Rome, New York, we have examples of trilobites retaining the antennæ and limbs in an extraordinary state of preservation.

Mud Bottoms. — As a rule the areas of mud accumulation are devoid of attached seaweeds and, since the water currents are here very slight, little food is brought to the animals that might otherwise live upon or in the mud. In consequence the mud areas have a scant life and are therefore known as the *desert areas of the seas*. These observations of the present marginal seas also help us to understand the dearth of life in the majority of the green, blue, and black shale deposits of epeiric origin. When fossils of bottom-dwelling types do occur, they are in thin zones and more often swimming or floating forms.

Sediments and Their Alteration

Kinds of Sediments. — In general it may be said that the sediments of seas are coarser in grain than the oceanic deposits, but of finer grain and far better assorted by the moving waters than the continental formations. The sediments of all strata are either

mechanically formed or of *organic origin*. The former embrace the *arenaceous deposits* such as the sandstones and sandy shales which together make about 15 per cent of the water-laid strata, and the *argillaceous deposits*, the mudstones, which constitute about 80 per cent of the sedimentaries (F. W. Clarke). The *organic deposits* make up only 5 per cent of the water-laid strata and consist of limestone, dolomite, chalk, marl, and the oceanic pelagic oozes. What percentage of the muds and organic deposits is permanently lost by the continents and added to the oceanic basins is unknown.

Deposition of Limestones and Dolomites. — The lime and magnesia carried in solution by the rivers to the seas are distributed far and wide by the marine currents. That small part which is taken out of the water through organic agency in the littoral is masked because of its dissemination through the thick deposits of these seas. For this reason it is usually said that limestones and dolomites are the deposits of the deeper waters and those far from the shore. However, back of the Keys of southern Florida, where the waters are warm and the land is limestone and but little above sea-level, limestone and oölite deposits may be seen accumulating on the very shore. In the past few years it has become plain that the main areas of limestone and dolomite formation are the warm waters, for in the tropical regions not only do the rivers bring to the sea more lime, but the oceans are also far richer in denitrifying bacteria (Fig. 335) and it is these micro-organisms that in their physiological processes throw down the main amount of lime carbonate. To this are added the structures made by the lime-secreting algæ, of which there are many kinds, by the coral reefs, and by other lime-using animals. The calcareous muds in the deeper water of tropical and subtropical regions, in depths of from 600 to 2000 feet or even more, have from 80 to 90 per cent of lime, and of this from 10 to 50 per cent originates in the floating Foraminifera, while from 2 to 40 per cent is from bottom-living Protozoa. Proceeding poleward we meet with less and less of limestone accumulation, though this is always locally dependent upon the temperature of the surface waters that again are so largely altered by the great oceanic currents.

Fig. 335. — The bacteria that cause the precipitation of calcium carbonate in the ocean (*Pseudomonas calcis*). Greatly enlarged. After Kellerman and Smith.

Nansen has directed attention to the hemipelagic muds of the central Arctic Ocean, which he says are devoid of large organisms and are brown in color, with only from 1 to 3 and rarely 5 per cent of lime. He states that this mud is a mineral deposit devoid of life other than a few bottom-dwelling Foraminifera. The muds of the Arctic waters off Europe show far more lime, from 25 to 40 per cent, with a maximum off Iceland of from 45 to 60 per cent, dropping at Jan Mayen again to 10 per cent. Most of this lime is from Foraminifera (*Biloculina*). It would further appear that more lime is present in the surface muds than in those beneath, an increase that may be due to the gradual warming of the climate in recent geologic time.

Diagenesis. — As limestones are of organic origin, naturally they should have an abundance of fossils, and most of them do. It is well known, however, that many are more or less crystalline, as are nearly all of the dolomites, and in this case fossils are usually absent or are so altered as to be almost unrecognizable. Here we are not dealing with metamorphism, because many such limestones and dolomites still remain horizontal and occur in areas unaffected by elevation and igneous injection. It is true that a process of alteration has taken place, but it was contemporaneous with accumulation and not ages afterward. The diagenetic changes are due to chemical alterations taking place on the sea bottom and in warm waters. The Globigerina oozes of the present seas show no alterations and, even though they are the *growth* of warm surface waters, are accumulated in the ice-cold depths of the ocean abysses. The limestones of shallow warm waters, as for instance many coral reefs, have lost most of their organic structures, and we learn by careful study that the carbonate of lime originally present in the form of aragonite has been converted into calcite. In addition, the original carbonate of lime in either form may be more or less replaced by magnesium carbonate and thus a calcium carbonate coral reef may be altered into a dolomite. Time, warm water, variable concentration of solutions, much oxygen, and a wealth of decomposing organic matter are the requisites that will completely alter calcareous organic accumulations into crystalline limestones and dolomites. This alteration has been called by Walther *diagenesis*, from words meaning *through* and *birth*, or, in other words, it is a rebirth through contemporaneous alteration.

Iron pyrite and marcasite concretions and fossils of black shales are also diagenetic products. Moreover, it has been held that the flints of chalk deposits are diagenetic in origin where the colloidal silica of sponges is progressively dissolved and redeposited about nuclei as flint and thus converted into these irregular lumps. On the other hand, the cherts of limestones develop near the surface in

the zone of the circulating ground waters during the process of weathering, and are therefore not of diagenetic origin. As chalk is porous to ground water, and as the flints occur in both horizontal and vertical attitudes, it is probable that they, too, are formed after the sediments are uplifted sufficiently high to permit the circulation of meteoric waters.

CHAPTER XXIV

EVOLUTION OF THE STARS AND THE SOLAR SYSTEM

Stars Seen by the Naked Eye. — What a wondrous sight are the skies on a clear dark night, especially in the rarefied air of a mountain top or in the dry climate of the desert! We see distinctly hundreds of quivering stars, large and small, variable in color, all set in the deep black of boundless space. The Milky Way extends across the whole sky like an irregular filmy cloud of silvery white, and it too consists of stars in various stages of their careers. The largest of all the apparent stars are, of course, best seen in the early evening and morning — Evening and Morning Stars, as we call them, though they are not stars but planets of our solar system shining by reflected light derived from the sun.

All of the true visible stars are self-luminous bodies and most of them exceed by far the dimensions of the sun, although the latter has a diameter of about 864,000 miles. This life-giving sun is the nearest star, and yet, though its rays reach the earth with considerable warming power, it is about 93,000,000 miles away. The nearest fixed star, on the other hand, is more than 200,000 times more distant than is the sun; nevertheless most people can see at any given locality at least 250 stars, and good eyes can make out about 800. In all that portion of the sky visible from the northern United States about 1600 stars can be discerned with the unassisted eye.

Stars of Astronomers. — The astronomers, however, by means of their marvelously delicate telescopes, spectroscopes, and photographic cameras, estimate that they have records of nearly 114,000,000 stars, and still this is by no means all, for as their apparatus is perfected more and more, the greater will be the depth to which they can penetrate into space and the greater the number of stars they will discern. There are also scattered through the heavens many dark stars, invisible because non-luminous, the approximate number of which no one knows, nor have we any knowledge of their planets and satellites, if such they possess. Space without limit, through which are moving countless systems of orbs in wondrous array — such is the majesty of the Universe!

New Stars. — It is known that all the stars are in motion in various directions, our sun with its retinue of planets moving toward Vega at the rate of 11 miles per second. This being so, why is there not the possibility of collision between the stars or between them and the unknown dark orbs, or at least an approach so near as to result in disruptive tidal strains?

Every now and then there suddenly appears in the sky, and mainly in the region of the Milky Way, a *nova*, a new or temporary star that lasts but a short time. It is the record of "a superb stellar catastrophe." Temporary stars have blazed up about twenty-six times since men began to write their records of the skies. The most famous is Tycho Brahé's star of 1572, which reached a brightness greater than any other star, but which, notwithstanding its brilliance, remained visible but sixteen months.

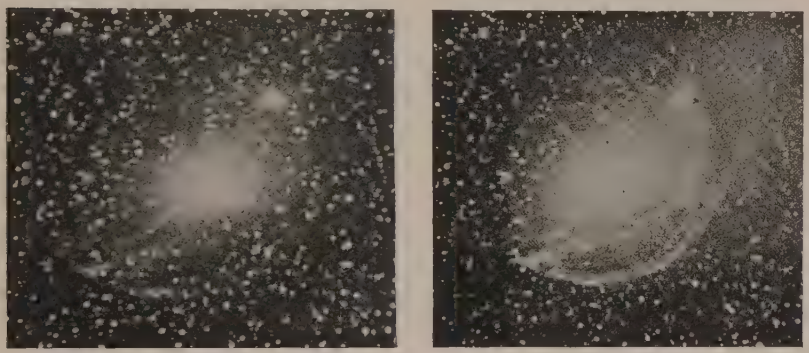


Fig. 336. — The new star in Perseus in 1901, showing expansion of nebulosity from September 20 to November 13. Photograph by Ritchey, Yerkes Observatory.

One of the most wonderful astronomic objects ever observed was seen in the constellation Perseus on February 22, 1901, when photographs made twenty hours apart showed a new star present only on the plate last exposed. The actual birth of the star, however, must have occurred about 1781, since it would take approximately 120 years for its light to reach the earth. Within a few days after the discovery of this star, its brightness grew to the first magnitude, and while it was fading it developed into a nebulosity (Fig. 336).

Stellar Evolution

Origin of Stars. — The light of the stars, when transmitted through the prism of the spectroscope, shows that their temperatures and the nature of their elemental matter vary enormously.

Stars apparently begin in nebulous matter, and it has been said that the nebulous clouds are the matrices, the primitive and uncondensed material out of which stars are made. As stars they are in the gaseous state, and further evolution takes place, through condensation and the loss of heat by radiation, into smaller, more complex, and hotter suns. It is thought that they will pass eventually into invisibility as dark orbs with cold exteriors.

The great nebula in Orion (Fig. 337) is thought to be in the first period in the history of a star, for here the gas is exceedingly

Fig. 337. — The great nebula in Orion, with irregular star condensing centers. Photograph by Ritchey, Yerkes Observatory; two-foot reflector, one-hour exposure.

tenuous and the stars condensing in it seem to indicate that the entire cloudlike nebulous mass is also in motion. From this primitive astral condition we pass to the

Helium Stars. — The spectroscope has brought out the fact that the spectra of stars increase in complexity as the cooling process continues. Through the study of the spectra it has been

learned that the gaseous nebulæ of the Orion type in their earlier development reveal dominantly helium.

Hydrogen or Sirian Stars. — Next in order of evolution, according to Hale, appear to be the white, or bluish-white, stars like Sirius, in which the spectrum is marked by conspicuous hydrogen lines, associated with inconspicuous ones of iron, sodium, magnesium, etc. These stars, though relatively condensed, are, however, much less dense than the sun. As the gaseous masses condense they lose through radiation a vast amount of heat and, surprising as it may seem, grow hotter. This is true so long as the star remains gaseous.

Solar or Metallic Stars. — Further condensation produces more and more of a thick absorbing atmosphere, and the consequent

Fig. 338. — Solar prominences during the total eclipse of May 28, 1900. Photograph by Barnard and Ritchey, Yerkes Observatory.

filtering of the stars' light causes them to take on a yellowish or reddish tinge. The hydrogen or Sirian stars previously noted do not possess dense absorbing atmospheres, and due to this fact and to their extremely high temperature, they are revealed to us as the white or bluish-white stars. Solar or yellowish stars, on the other hand, are thought to have attained stellar maturity, and like the sun have thick absorbing atmospheres; their interiors, however, are still gaseous, though under strong compression. The sun is one of the metallic stars, somewhat hotter than the reddish yellow or Arcturian type, and the spectroscope reveals in it the presence of vapors of iron, sodium, magnesium, calcium, hydrogen, and many other substances known on the earth. The sun is

therefore a star practically identical in chemical composition and in physical constitution with many other stars in the heavens.

Hale describes the appearance of the sun at times of total eclipse as follows: "Red flames, sometimes reaching heights of several hundred thousand miles, may be seen rising from a continuous sea of flame, which completely encircles the Sun. [They shoot outward with velocities of hundred of miles per second. See Fig. 338.] These are the prominences, and the continuous mass of flame from which they rise is the chromosphere. Extending far beyond these flames into space, sometimes to a distance of millions of miles, is the corona, which shines with a silvery luster somewhat inferior in brightness to that of the full Moon."

Helmholtz calculated that the sun's heat could be supplied by the shrinkage of its vast bulk under the influence of its own gravitational attraction. An annual shrinkage of only 300 feet in the solar diameter would be transformable into enough heat energy to maintain the observed radiation. This energy of the sun is conveyed through the ether of space and attains the earth in eight minutes and twenty seconds, or at the rate of 186,000 miles per second.

Carbon or Antarian Stars. — The stars in their continued evolution beyond the solar stage eventually fade further and further toward invisibility. From the yellowish stars we pass to those of an orange or red color, the spectra of which reveal marked carbon lines. The latter is the last period of stellar visibility.

Dark Stars. — Finally the evolution continues into the dark or invisible stars, of which many are known to exist by the gravitative disturbance which they exert upon the neighboring stars. The last stage will be the formation of a hard outer shell, but no life will be evolved because there will be no light to supply the necessary environment for organisms. The original motion, however, will continue, and therein lies the possibility of a future cataclysmic approach to some other star.

Nebulæ

Number of Nebulæ. — These luminous clouds of matter are strewn in space less thickly than the stars, and though enormous in size but two can be seen by the unaided eye (Orion and Andromeda). The largest is the great nebula of Andromeda, hundreds of thousands of times greater in diameter than the distance from the earth to the sun, yet visible only on the clearest of nights, due to its extreme tenuity and tremendous remoteness. Hale says it is the most interesting object in the heavens.

Keeler estimates that within the reach of the Crossley reflecting telescope fully 120,000 nebulæ will be revealed, with photographic assistance, and Poincaré states that eventually astronomers will know more than a million nebulæ.

Nature of Nebulæ. — Nebulæ are filmy masses of shining gas, with or without diffused solids, and possess an inconceivable tenuity; in fact they are almost without any density whatever (Figs. 337, 339–341). They are thought to be in a state of change, condensing with extreme slowness into nebulous stars or clusters of stars. In some, no condensing centers are seen at all, and they then appear as the thinnest fleecy clouds, but in most of them occur one or more brighter though hazy nuclei. There are a number of fundamentally distinct kinds which may be discussed as follows:

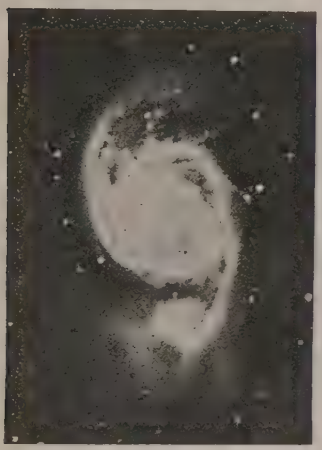


Fig. 339. — A brilliant spiral nebula in Canes Venatici. Photograph by Ritchey, Yerkes Observatory; two-foot reflector, six-hour exposure.

Fig. 340. — A typical spiral nebula in Pisces. Photograph by Lick Observatory.

Green Nebulæ. — The rarer of these gaseous and luminous masses are known as the green nebulæ, nearly all of which are found in the Milky Way. They are characterized in the spectroscope by bright lines, the brightest of which are green in color and represent nebulium, an element known only in these nebulæ. Other lines indicate hydrogen and helium, but no metals seem to be present. The cause of their luminosity is unknown, and is probably not heat; their temperature may be near absolute zero. As the green nebulæ appear to have no direct bearing on the evolution of the solar system, they need not be further considered.

White or Spiral Nebulæ. — The greater number of nebulæ, however, are known as the white nebulæ, because their white light gives continuous spectra (Figs. 337, 339–341). The material, though solid, Chamberlin conceives to be in a finely divided condition.

The cause of the white light is unknown, and opinions differ as to the elemental constitution of these nebulæ.

The dominant and possibly even the universal form of the white nebulæ is the spiral, and they are therefore referred to also as

Fig. 341. — A spiral nebula in Ursa Major. Photograph by Ritchey, Yerkes Observatory; two-foot reflector.

the *spiral nebulæ*. The one in the constellation of Andromeda, as has been said above, is the greatest of them all. " From the superior number of spiral nebulæ it is a safe inference that their pecu-

liar forms represent some prevalent process in celestial dynamics. This is, in itself, a reason why research should turn to them by preference for the origin of the present solar system." (Chamberlin.)

The significant feature of these nebulæ is the presence "of two dominant arms that arise from diametrically opposite sides of the nucleus, and curve concentrically away. . . . There are often more than two arms in the outer part, and there is much irregularly dispersed matter." Throughout the mass, but more especially on the arms, are partial concentrations of matter spoken of as the *nebulous knots*, while otherwise the diffuse nebulous matter is unequally distributed. We seem to see here independent parts revolving about the common center of gravity, as though they were planetoid bodies, and Chamberlin goes on to say that if this were certainly known to be the case, they might well be called *planetesimal nebulæ*. The importance of this interpretation will be seen later.

The tenuity of these nebulæ shows that they are thin and disc-shaped and that the matter is also irregular in distribution within the discs, all of which conforms to the mode of distribution of matter in the solar system.

Meteorites

We must here digress a little to study the meteorites. On almost any dark night, but more especially during August and September, may occasionally be seen brilliant white or green streaks of light shooting with high velocity and in diverse directions through the skies. These fiery lines, popularly called "shooting stars," are caused by bodies of solid matter varying in size from a fraction of an ounce to a hundred or more tons, but averaging about the size of a grain of wheat (Figs. 342, 343). They are moving swiftly through space and have come into contact with the atmosphere of the earth. The velocity of impact is so high, averaging between 20 and 30 miles per second, that the meteors are heated to the point of dissipation as a luminous gas by the friction generated in passing through the terrestrial atmosphere. Thus they become visible only at the moment of their dissolution, and this is dependent upon the accident of collision with the earth.

On certain nights of the year and especially in certain years, the number of meteors is enormously increased, and they appear to radiate from some one part of the sky like a rain of shooting stars. At such times the earth in its motion around the sun is passing

through a swarm of meteors also moving together about the sun. Such a swarm is called a meteoric swarm.

Meteorites are wanderers from other solar systems attracted to

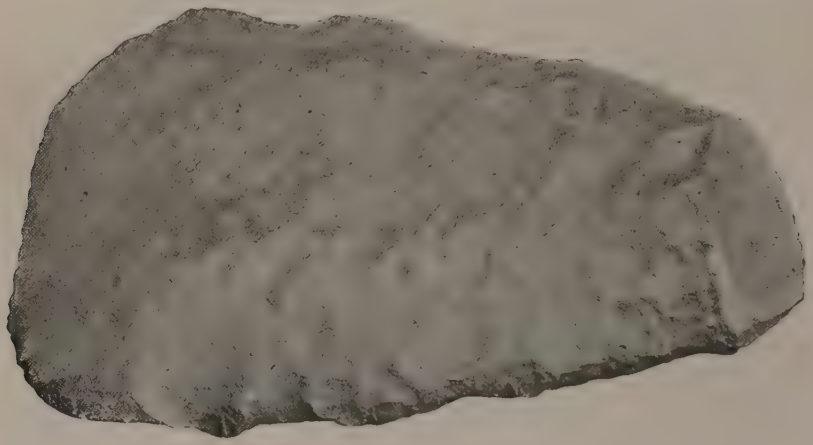


Fig. 342. — The Gibbs nickel-iron meteorite found in Texas. Weight 1635 pounds. At Yale University.

Fig. 343. — A stony meteorite that fell at 5 P.M. on May 26, 1890, in Winnebago County, Iowa. In exploding it broke into several thousand fragments, more than eight hundred of which are here shown. The largest piece weighed 80 pounds. At Yale University.

the sun and earth from outer space. They bring to us samples of the bodily constitution of the former and the proof that they are closely related in their chemical elements to our own sun and

earth (Figs. 342–344). For the relations of meteors to comets see the next chapter.

Chamberlin regards meteorites as "but an incidental result of stellar and planetary action. Their genesis is wholly a secondary matter, and furnished no ground for regarding meteorites as the parent material of great nebulæ or of stellar systems. . . . This scattered matter is presumed to be picked up bit by bit by all the larger bodies, as is being done daily by the earth."

Fig. 344. — Section of the Grand Rapids, Michigan, meteorite, showing the coarse crystallization of the nickel-iron (Widmanstätten figures). Natural size. At Yale University.

There is a great variety of meteorites, but the larger number of falls center around two main types: (1) the common nickel-irons, often of great weight (Figs. 342, 344), and (2) the rarer and usually smaller chrondritic or stony meteorites (Fig. 343). Their micro-structure shows their crystalline aggregates or chondri to be usually fragmented or brecciated. There is also an absence of water and hydrates, free oxygen, quartz, orthoclase, mica, etc., but they show the presence of volatile and combustible hydrocarbons, and of certain unstable chlorides, sulphides, and phosphides unknown on the earth.

Theories of Solar Origin

Man, with all of his limitations, has throughout long ages been asking whence came the earth, his home, and the sun and stars in the canopy of the heavens above it. It is only within the past few centuries, however, that this inquiry has been pursued along scientific lines, and among the older peoples "the limit of the spiritual field of vision determined the wider or more circumscribed flights of imagination."

The downfall of the Roman Empire and the long succeeding

periods of constant warfare, along with climatic changes, prevented all far-reaching philosophic endeavors during the first twelve centuries of the Christian era. The next expansion in the realm of thought came with the revival of learning that spread throughout Europe in the fifteenth century, when universities, learned societies, and academies were founded. Then methods of dogmatism were cast aside and the modern scientific methods of attaining knowledge took their rise.

Nebular Hypothesis of Kant. — Astronomy and physics received a great impetus from Newton's principle of universal gravitation, given to the world in 1687, a principle that led to a sound conception of the evolution of the solar system. This Newtonian principle was the basis of Emmanuel Kant's nebular hypothesis, which that professor of mathematics and physical geography at Königsberg presented in 1755. His *Naturgeschichte des Himmels* appeared anonymously and remained in oblivion for ninety years, to be finally unearthed from neglect by Von Humboldt.

Kant, according to Iddings, conceived that the universe might have been developed out of chaos and that space was filled with fundamental material highly varied as to mass, density, and power of attracting other particles. He argued that since the planets and their satellites moved in strict conformity with one another and in definite relation to a central sun, with vacant spaces between them, there must have been a diffusion of their substance through space, and a subsequent segregation into planetary masses.

The attraction of the particles for one another would occasion motion in all directions throughout the swarm. The denser would in time become nuclei of condensation. Finally there would thus result zones or rings of discrete particles segregating into condensing nuclei, which upon further condensation become planets and satellites, the preponderating central nucleus becoming the sun.

Heat, he held, was formed through cosmical attraction according to laws that are chiefly chemical, and gases on condensation liberate heat. The amount of heating must be proportional to the mass of the growing body, and to the rapidity at which the mass condensed. Consequently the greatest heat would be in the central body or sun.

Nebular Theory of Laplace. — The nebular hypothesis was again independently developed by the Frenchman, Laplace, in 1796 and further modified in 1824. This celebrated explanation of the origin of the solar system, as Hale states, has dominated the world's thought since the very date of its publication. Iddings has re-

studied Laplace also in the original and from his work has been taken the following:

Laplace imagined the planets and satellites, because of the similarity in their rotations and in the planes of their orbits, to have been derived from some vast fluid of immense attenuation which surrounded the sun like an atmosphere and extended beyond the outermost planet, Neptune, a body 2,800,000,000 miles away from the sun. This nebulosity was supposed to have possessed a high temperature, and was so attenuate that one may scarcely conceive of its existence. It revolved about the central nucleus

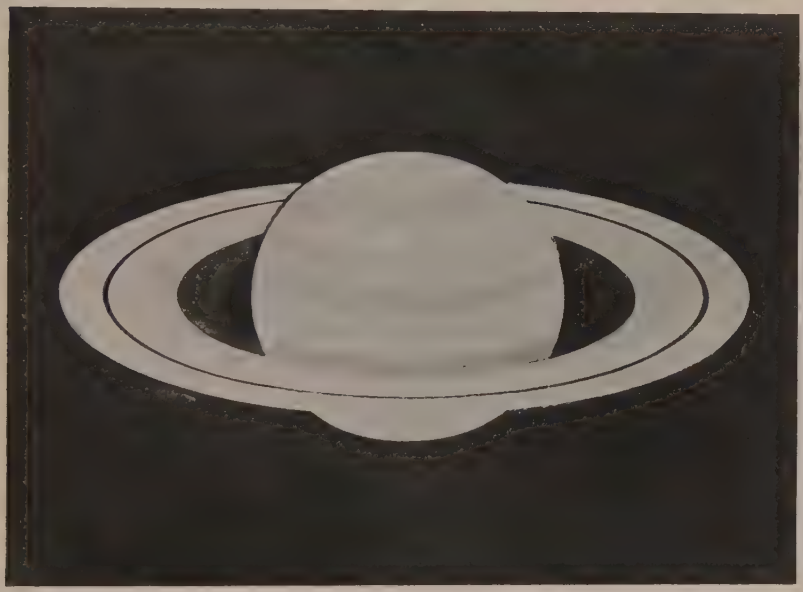


Fig. 345. — Saturn as seen with the 36-inch refractor. Drawing by J. E. Keeler, Lick Observatory. The outer ring has a diameter of 172,610 miles, a width in its plane of about 11,000 miles, and a thickness estimated at 50 miles. The space inside the outer ring is 2200 miles, and the second ring is about 18,000 miles wide. The dark or crape ring is about 11,000 miles wide, with its inner edge less than 6000 miles from the surface of the planet. The equatorial diameter of the planet is 76,470 miles. (Moulton.)

or sun and assumed a disc-like form. In the course of time it successively gave rise to equatorial zones or rings, resembling those of Saturn (Fig. 345), and these rings segregated into nuclei and eventually condensed into planets. In their turn the planets condensed and repeated the process of annulation, thus giving origin to the satellites. In the case of the planetoids, the very small planets also

known as minor planets or asteroids, the masses of the broken rings did not unite into a planet, but each part formed an asteroid. On the other hand, some of the rings of Saturn did not break but remained as rings. To account for the eccentricities in the orbits and their deviations from one plane of revolution, he imagined that there were numberless variations in the temperature of different parts of the nebula and in the densities of the nuclei, that is, it was a nebula that was clearly heterogeneous both as to density and temperature. He conceived of the earth as having passed from a gaseous to a liquid, and finally a solid condition, with absolute rigidity.

Objections to Laplace's Theory. — Even though the nebular hypothesis of Laplace has so long dominated the world's thinking, objections and difficulties were brought forward at various times during the nineteenth century. According to Barrell, we may divide these into *fundamental objections* and *modifying objections*. Of the fundamental ones, perhaps the most readily appreciated is that concerning the energy of rotation of the system. This and others have been developed by Moulton, who worked with Chamberlin upon the larger problems of earth origin. The argument as developed is briefly as follows: If the mass of the solar system at one time revolved as a unit and at the same time condensed, toward the center it would gain in angular velocity of rotation, as is seen when agitated water converges toward the central part of an eddy. By virtue of such condensation and angular acceleration, the equatorial belt of the nebula would at last reach a critical state when the outward or centrifugal force balanced the inward gravitative force. After this stage was reached, the matter could no longer converge toward the center, but would be left circling in space about the center. The remainder would continue to condense, but more and more would reach the critical equatorial velocity and be left behind. Yet contrary to this expectation, the bulk of the planetary matter and by far the greatest part of the rotational energy of the solar system about the solar axis resides in the giant planet Jupiter. All of the interior or minor planets, among which the earth is included, are negligible in comparison.

Most telling of all, however, in this line of argument, is the slow rotation of the sun itself. Instead of being a swiftly revolving and highly oblate body, with its equatorial zone in a critical gravitative condition, it revolves leisurely once in twenty-five days; so slowly, in fact, as to have no measurable departure from the spherical form. Now mathematical analysis shows that the *energy*

of rotation of any body in space cannot be increased * or diminished by internal motions. It can be diminished only by a frictional resistance of space or by tidal forces raised upon or within it by some great external body. Neither of these conditions can be invoked. Therefore the matter of the sun revolved with but little energy through all its history, and the antecedent solar nebula, if it included the planets, could never have revolved as a unit. Hence the matter of the planets, even before their aggregation, revolved separately from the sun. It is difficult, then, to regard them as left behind in the primordial contraction of the solar matter from a widely diffused nebulous state of which the planets were a part.

To appreciate fully all the arguments that bear against the Laplacian hypothesis, Chamberlin and Salisbury state that the student must have a knowledge of celestial mechanics and of the molecular activities of gases. Because of this difficulty, all of the objections will not be recited here. In addition to the fundamental objections just discussed, the following are taken from Chamberlin and Salisbury and from Hale:

(1) No nebulæ closely resembling the annulated solar nebula have yet been discovered. The type thought by Laplace to support his theory has since been found to be spiral in the great majority of cases. (2) If the original solar nebula extended to the orbit of Neptune it would have been so extraordinarily tenuous as to have made it impossible for separate rings to have formed. In a hot gaseous nebula, moreover, the molecular activities would cause the molecules to separate from the parent nebula one by one. It has also been shown that the original solar nebula may have been a gas or a swarm of meteorites and that its temperature may have been low and not hot. (3) If the planets developed from the ring system as postulated by Laplace, they should rotate in the opposite direction from the parent body, the sun, and this is not their present condition. (4) The satellites should all revolve about their planets in the direction in which the planets rotate on their axes; but the ninth satellite of Saturn revolves in the opposite direction. (5) Phobos, the inner satellite of Mars, revolves about the planet three times while the planet rotates once. The Laplacian hypothesis requires that its velocity should be less than that of the planet's surface. (6) The rings of Saturn are not gaseous, but were shown mathematically by Maxwell in 1859 to be necessarily composed of small bodies like meteorites. Further, the rings do not revolve like solid bodies, as stated by Laplace; on the contrary, the inner parts of the rings are traveling faster than the outer, and each of these swarming meteorites is moving at the velocity a satellite would have at the same distance from the planet. (7) The masses of the various planets, as well as the densities of the rings from which they are supposed to have been formed, are shown to be entirely out of harmony with what the hypothesis would lead us to expect. (8) Even if rings

* Increase of *velocity* due to condensation should be distinguished from increase of *energy* of the rotating body.

had been formed, Moulton has shown that it would have been impossible for the nebular material to draw together into a planet. (9) He has also shown that the diffuse earth-moon ring, with its low power of attraction, could not have held any atmospheric gases or water-vapor. Even such concentrated bodies as the moon and Mercury are now unable to hold atmospheres. See also page 249.

Hale concludes: "It can hardly be denied that Laplace's idea of the development of the solar system must be reconstructed or abandoned."

CHAPTER XXV

ORIGIN OF THE SOLAR SYSTEM UNDER THE PLANETESIMAL HYPOTHESIS

By Joseph Barrell

Survey of the Problem

The logic of all branches of science points to the existence of some system of evolution of the universe, its complete nature hidden in the vastnesses of time and space, but nevertheless developed in accordance with nature's laws.

Nebular Hypothesis. — The achievement of the eighteenth century which expressed man's efforts to find a solution for this great problem was the nebular hypothesis. It measured a vast advance in ideas beyond the ancient and medieval conceptions of the mode of origin of the universe, but, as has been shown, as an attempt to account for the origin of the planets, it meets with grave difficulties when analyzed. It was founded essentially upon the conception of the condensation of matter, originally existing in a diffuse state, through gravitative attraction. A further essential part of the hypothesis was the conception of a nebula as a unit body, distended by heat, and revolving as a single mass.

Distinctive Features of the Planetesimal Hypothesis. — But toward the end of the nineteenth century, some, of more penetrating vision, began to see also the evidences in the stellar universe of prodigious forces of an opposite nature, not those of attraction, but of repulsion. The tails of comets blown away from the sun with high velocity, and the streamers which compose the solar corona, the envelope of the sun, seen only in eclipses, pointed to the repellent forces of electricity and light. New stars, the high velocities of some other stars, and the forms of certain star clusters seemed further to suggest a possible mode of origin through vast explosive and therefore repellent forces contained within the stars themselves. The tides also are the expression of forces which, though weak as shown upon the earth, tend toward the disruption of the bodies upon which the forces act.

The sun and moon raise terrestrial tides by virtue of the pull of gravity and thus modify that spheroidal form of the earth which is given by its own gravity and the centrifugal force of its revolution. Suppose, in other examples of heavenly

bodies, the tidal pull to be many times stronger, the self-gravitative cohesion to be many times weaker. A limit will be reached at which the body may be pulled to pieces. This phenomenon, which has been actually observed in the case of comets passing close to the sun, has been called *tidal disruption.*

It remained for Chamberlin and Moulton to apply the theory of tidal disruption to the explanation of those nebulæ which exhibit a spiral form and to see in this an hypothesis which might explain the evolution of that planetary system to which our earth belongs. This, the *planetesimal hypothesis,* is fundamentally different from the nebular hypothesis in that it supposes as a beginning a disruptive expansion of matter from some central body, an ancestral sun, the planetary matter being conceived as thrown out from a sun and assuming the form of a spiral nebula, not, as under the nebular hypothesis, as being the residue left behind from a primal condensation of matter into a sun. The form of the nebula was, in this new conception, supposed to be maintained through the motion of its particles moving in orbits, and not by the resistance of heated matter to condensation. After being thrown out, however, processes of local convergence came into operation, by means of which the scattered nebulous matter, whose constituent particles may be called planetesimals, became drawn into nuclei. The nebula consisting of planetesimals passed thus into a planetary system. When this stage was reached there began the geologic history as distinct from the cosmic history of the earth.

By the very naming of a scientific conception as an hypothesis, it is to be understood that although therein lies, it is thought, a contribution toward further knowledge, there is still much which remains unknown. The truth must be tested and enlarged by future generations, the conceptions remodeled and separated from the adherent errors. But the value of an hypothesis lies in the degree to which it coördinates and explains a large number of facts, and in the fertility of suggestions which it offers toward new lines of investigation. Judged by these tests the planetesimal hypothesis is the crowning achievement of the nineteenth century in the field of cosmic philosophy.

What then make up the warp of theory and weft of fact which are woven together to make the fabric of this hypothesis?

The Order Among the Planets

Nature of the Planets. — The points of light seen on a starry night are of two fundamentally different natures. The true stars, of all grades of brightness and innumerable to the eye, are distant

and self-luminous suns. They are distinguished by their apparently fixed relations in the heavens through all the centuries, and by the trembling or scintillation of their light as a result of its passage through the terrestrial atmosphere. These qualities are due to their inconceivable remoteness from us, a remoteness which renders inappreciable, except to the astronomer, their really swift motions, and causes their glowing discs, though millions of miles in diameter, to appear as mathematical points of light, the rays from which are momentarily deflected from the eye by the varying refraction due to the slightest motions of our atmosphere.

Contrasted with the *stars* there are five bodies visible to the naked eye which to the casual observer appear as stars, but are in reality of a wholly different nature. These are the *planets* Mercury, Venus, Mars, Jupiter, and Saturn, distinguished by the fact that they wander in a certain pathway through the heavens, the more swiftly moving showing a change of position among the stars perceptible to the unaided eye even in a few nights, while the slower ones show an appreciable shifting only from month to month, or year to year. Their light, furthermore, is clear and steady, owing to the fact that they have appreciable discs, readily visible in the telescope. In spite of the disturbances in the terrestrial atmosphere, light from one or another point of the disc is consequently continually reaching the eye of the observer.

Two of them, Venus and Jupiter, are, except for the sun and moon, the brightest objects in the heavens, but the telescope has added to the number of the planets two large ones, Uranus and Neptune, invisible because of their distance, and, in one zone of intermediate distance, a swarm of smaller bodies, the *asteroids*, better called planetoids. The planets are bodies like the earth and moon. The earth is in fact one of them and the moon is its satellite. All revolve in nearly circular orbits about the sun. In size they sink to vanishing insignificance in comparison with the sun or any other star. Their distances from the sun and from each other are also almost infinitesimal in comparison with the distances which separate the stars. They shine by light reflected from the sun, and as all are attendant upon the sun, they form a common system, the solar system. Their mutual relations are therefore of fundamental significance in the study of those events which led up to the origin of the earth.

TABLE OF THE PRINCIPAL ELEMENTS OF THE SOLAR SYSTEM

The facts regarding their size, their distance from the sun, and the inclination and position of the plane of their orbit with respect to the orbit of the earth are tabulated as follows:

The Solar System.

	Name.	Diameter, miles.	Density, water = 1.	Mean distance in millions of miles from the sun.	Inclination of plane of orbit to earth's orbit.
	Sun	866,400	1.39	.....	7° 15′*
Minor planets	Mercury	3,030	?	36	7 00
	Venus	7,700	4.85	67	3 24
	Earth	7,918	5.58	93	0 00
	Moon	2,162	3.40	0.239†	5 09
	Mars	4,230	4.01	141	1 51
	Planetoids	0 to 485	?	200 to 400	0 to 34 42
Major planets	Jupiter	86,500	1.33	483	1 19
	Saturn	73,000	0.72	886	2 30
	Uranus	31,900	1.22	1782	0 46
	Neptune	34,800	1.11	2792	1 47

* Inclination of sun's equator to earth's orbit.
† Mean distance of moon from earth.

Notable Planetary Relations. — That the orderly nature of this system implies some mode of evolution was seen by the framers of the nebular hypothesis. The more notable of these relations, following the summary by Young, are:

1. The orbits are all *nearly circular*.
2. They are nearly *in one plane* (excepting the cases of some of the little asteroids). See Fig. 200.
3. The revolution of all is *in the same direction*.
4. There is a curiously *regular progression of distances from the sun* (expressed by Bode's law, which, however, breaks down at Neptune). See foregoing table.
5. There is a rough *progression of density*, increasing both ways from Saturn, the least dense of all the planets in the system.

As regards the planets themselves, we have:

6. The *plane* of the planets' rotation, the plane of their equators, *roughly coinciding with those of the orbits* (probably excepting Uranus).
7. The *direction* of the rotation of the planets about their polar axes *the same as that of their revolution in their orbits* (excepting probably Uranus and Neptune).
8. The *plane* of orbital revolution of the satellites of each planet *coinciding nearly with that of the planet's rotation*, its equatorial plane.
9. The *direction* of the satellites' revolution in their orbits also *coinciding with that of the planet's rotation about its axis* (excepting the ninth satellite of Saturn).
10. The largest planets rotating most swiftly.

The Order Among the Stars

Significant Relations of the Stars. — The sun, as has been learned in the previous chapter, is but a star and a member of the stellar system. What are the orders of magnitude, of number, of size, of distance, of speed, of duration among these countless orbs, and how do these relations enter into the problem of the origin of the earth as one of that retinue of planets which attend upon the sun?

The stars of our system are estimated to be more than a hundred million in number. Those whose diameters are known range from somewhat below a million to upward of ten million miles and more.

Many of the stars are in reality double or multiple stars, consisting of companions so close that the two or more appear as one star to the naked eye, or even under the highest power of the telescope, the evidence of their composite nature being revealed only through the analysis of their light by the spectroscope. These double stars revolve swiftly about each other, but such internal motions must be sharply distinguished in thought from the streaming or drifting of the stars as parts of the great stellar system. Relatively to the sun they are found to move through space with speeds averaging between 10 and 30 miles per second, but ranging from less than 10 to more than 200 miles per second. They do not move, however, singly and in closed orbits, but rather in broadly scattered groups whose paths are almost straight lines. These courses of the stars must slowly curve under the aggregate attraction of the millions of stars, but can never return into themselves. The paths of groups of stars intersect other groups and are to some extent interwoven among themselves. With the passage of millions of years, the stars thus continually enter into new relations and build new configurations in the skies: a myriad host of stellar fireflies, the living and the dead, streaming through space hundreds of millions of miles per year.

Although the stars are so great in number, their distances from each other average tens of millions of millions of miles, those in our part of the stellar system averaging between sixty and eighty trillions. The star nearest to the sun, α Centauri, happens however to be at a lesser distance of about twenty-six trillions of miles.

Considering the numbers, the velocities, and the distances of the stars, what are the chances of collision between them, or of approach so close as to exercise upon each other strong tidal forces?

To bring down the dimensions of the universe to finite comprehension, we must divide the scale of nature by a thousand million. Then the earth would be represented by a pebble half an inch in diameter, circling once a year about a sun 4.5 feet in diameter, at a distance of 500 feet. The nearest star, α Centauri, would on this same scale be seen as two spheres revolving about each other at a distance apart equal to 2 miles, and each comparable in size to the sun. This double star would be situated at a distance of about 25,000 miles from our planetary system with its sun, but the other stars in this part of the stellar system would be separated from each other on the average by more than twice this distance. The Galaxy, or Milky Way, seems to be the outer zone of our stellar system, and its dimensions are only vaguely known. On this new scale it might be found to be encompassed by a circle of a hundred million miles diameter, or it might be more or less.

Chances of Close Approach. — The motion at any instant of any individual star is the result of its motion inherited from the past plus the attractions of all the matter in the universe pulling upon it in the present. If two bodies without previous motion were to be attracted toward each other, and were able to ignore the gravitative pull of all other bodies, they would move in a straight line toward each others' centers with ever-increasing velocity until collision would result. But the least inherited motion in any other direction, or the least deflecting pull upon one of them more than upon the other by other bodies would prevent to that degree a central collision, or in almost all cases any collision whatever. Now the velocities of the stars through space at great distances from each other are so great that individual stars can have almost no attractive influence upon each other. They must move in nearly straight lines past each other unless they happen to pass within a thousandth part of their average distance. It is seen then that the chances of close approach depend primarily upon the accidental crossing of their paths and only secondarily upon their mutually attracting each other. For this reason the chance of actual collisions may be regarded as absolutely negligible even considering the vast number of stars. Approach sufficiently near to generate strong tidal forces would, however, have occurred to a considerable number out of the hundred million or more of stars which are known to exist in the stellar system, but for any one individual star the chance of such approach even in a billion years would be very small. It is thought, however, that this happened once to our star, that is, to our sun of that time, in the distant past and from that disruptive tidal force was born our system of planets. Fortunate indeed has been our planetary fate, for not only did this happen so early in the sun's career that his radiant energy has been able to endure through all the ages

needed for organic evolution, but the spacing of the stars is so wide and the chance of approach so rare that no other of them has since advanced sufficiently near to throw this system into disorder, or disrupt and sweep away the earth and its sister planets as a wasted effort, and start the re-creation of a new heaven and a new earth.

The Forces of Tidal Disruption

The next question to be discussed is, Why is it that spiral nebulæ are the stellar responses to tidal forces, a fiery salute in recognition of the passing of another star?

Principles of Tidal Action. — Let M and N in Fig. 346 be two bodies passing each other in space and consider the action of the larger on the smaller. According to Newton's law the bodies attract each other directly as their masses and inversely as the

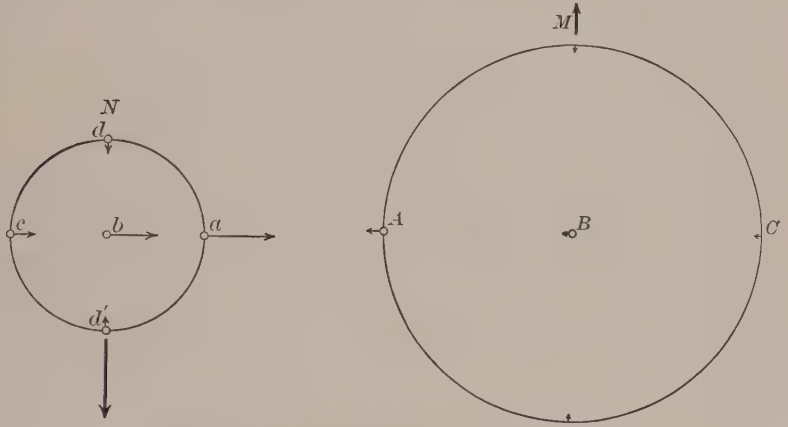


Fig. 346. — Diagram to illustrate tidal forces.

square of their distances, causing them to swing toward each other while passing by, but soon losing influence as they separate in their journeys through space. Consider three particles, a, b, c, on the line of attraction, taking them as separate parts of the smaller body. But a is nearer to M than is b, and b is nearer than c. Therefore if we represent the relative attractions by lines, these lines will correspond to the distances which the particles would move in a given time if free to obey the attraction of the other body. The line at a is longer than that at b and the latter is longer than that at c. If N was not bound together by its own gravity or rigidity, a, b, and c would therefore drift apart and fan out while passing M. Consider that rigidity is negligible, as in a

fluid globe; then, if a minus b, or b minus c are quantities which become greater than the self-gravitative force of N holding together a and c, the unity of the body becomes destroyed. The problem, however, is not quite so simple, since the influence of all other points in N must also be considered.

As the nearer part of the body is pulled from the center, and as the center is pulled from the farther side, there will, further, be two simultaneous tides of approximately equal height, but on opposite sides of the distorted body. They tend to be always on the line joining the two bodies. Thus, on the earth there are two tides on opposite sides, but the revolution of the earth on its axis, like a car wheel under two opposite brake-shoes, gives an apparent effect, to one on the surface of the earth, of a revolution of the tidal wave. As a result of the equal tides at opposite ends of a diameter there are, on any part of the ocean, two high tides in twenty-four hours.

Relations of Comets to Meteoric Streams. — In the previous chapter the meteorites were described and it was also stated that from time to time the earth in its motion around the sun passes through swarms of meteors.

Comets, compared to the earth or moon, are also small bodies. They fall or move toward the sun from outer space, swinging about it and receding again in highly elliptic or parabolic orbits. While in the vicinity of the sun, the nucleus or center develops gaseous envelopes which are driven away from it as fast as formed and constitute the familiar tails of the comets. Their lack of power to retain gases is a mark of their weak gravitative cohesion, which in turn is owing to their small mass. In passing close to the sun they would exhibit, except for their small size and the solid nature of their nucleus, the phenomena which would be shown by two passing stars. On account of these differences, however, the forces of tidal disruption work on them in another way. It has been found that a number of comets possess the same orbits as the meteoric streams (swarms of meteors), but the latter become visible to us only by the collision of their component meteors with the atmosphere of the earth. Many other meteoric streams, we infer, must therefore exist in the solar system unknown to us. The inference is strong that those comets especially which repeatedly pass too near the sun become disintegrated by tidal disruption, the action continuing upon each return until they become broken into fragments of a small size which are spread out as meteors along the cometary orbit.

Mode of Tidal Disruption in Stars. — A star is characterized by its enormous size and mass and by the possession of a gaseous constitution. The diameter and density are dependent upon the balance at every point between the tremendous expansive forces of internal heat and the equally great compressive forces due to its own gravity. If it contracts, then its surface and each component shell below comes nearer to the center, the effect of gravity upon

any shell accordingly increases inversely as the square of the new radius, and a higher internal temperature becomes necessary to balance the higher gravitative force. From this there results the paradox known as *Lane's law*, — that so long as a body maintains a gaseous constitution its temperature must rise as it contracts, even though at the same time it is radiating heat. The temperature of the interior must furthermore be higher than the temperature of the surface, because of the greater compression with depth, as is illustrated in the different strata of the terrestrial atmosphere. In those convective or slow boiling movements which are necessary in the sun and other stars in order that they should be able to maintain their surface radiation, there is then a constant liberation of energy from the depths and a system of balanced motion which if disturbed could lead in any star to an enormous explosion and blowing out of material from it.

The tide-generating force varies directly with the mass of the disturbing body and also with the radius of the body disturbed. It varies approximately inversely with the cube of the distance between the centers. The deforming force is, furthermore, greatest in the interior because the tidal forces acting on the zone at right angles to the line of force have a component which tends to squeeze in the points d, d' of Fig. 346 toward the center. The gravitative control is accordingly weakened along the line a, b, c, and is strengthened in the directions at right angles. Now apply this principle to the gaseous balanced nature of a star, and it is seen that the gaseous expansion in the line a, b, c is no longer exactly balanced by the gravitative compression, and the unbalancing is greatest in the center, where also is the region of highest compression and highest temperature. The effect is as if one squeezed a syringe bulb with orifices for exit at both ends, a bulb, however, like an air rifle, filled with gas compressed to an explosive degree.

A better analogy in some ways is supplied by the action of a geyser. As explained on page 219 of this book, increased pressure raises the boiling point of water. In a water column pressure increases with depth. Here in a natural water pipe more or less vertical, the deeper water is restrained from exploding into steam because of the pressure from the weight of the water above. But let the pressure through all the deeper parts be diminished by the upper part reaching the boiling point, turning into steam, forcing out the water from the upper part of the column, and replacing it by the substance of lower density. The whole column then becomes unbalanced, all parts flash into steam, and eruption of the geyser begins with explosive violence, the deeper water producing the most vigorous action. To revert to the exploding gaseous sphere, it is seen that, although all forces on the line a, b, c due to the attraction of M are directed toward

M, the tidal force due to *a* minus *b* and *b* minus *c* will tend to expel matter equally in both directions from the center. It is like a double geyser operating simultaneously from both ends of a diameter.

Tidal Disruption of the Ancestral Sun

Solar Prominences. — We have seen that the sun shoots out prominences to heights of nearly 300,000 miles, and at velocities ranging up to 300 miles per second. These phenomena indicate the enormous elastic and explosive energy resident in the sun's interior, an expansive potency held in restraint by the equally prodigious power of the sun's gravity.

Possible Disruption of the Sun into a Spiral Nebula. — Chamberlin states that " If, with these potent forces thus nearly balanced, the sun closely approaches another sun, or body of like magnitude . . . the gravity which restrains this enormous elastic power will be *reduced along the line of mutual attraction.* At the same time the pressure transverse to this line of relief will be increased. Such localized relief and intensified pressure must bring into action corresponding portions of the sun's elastic potency, resulting in protuberances of corresponding mass and high velocity. Dynamic considerations seem to make it clear that the sun might even thus be wholly disrupted, if the body to which it approached were much superior to it in mass and the approach were very close." Apparently a fraction of one per cent of the sun's mass would amply suffice if shot out as protuberances to make up the material necessary to form the planets and satellites of the solar system, but this may be the residue left from a far greater quantity of solar matter which took part in the tidal explosion. Thus Chamberlin conceives that a spiral nebula, having two dominant arms on opposite sides, would arise from the simple event of a close approach. It is to be expected that the arms would be knotty, that is, contain in places more condensed material or nuclei resulting from irregular pulsatory explosions of the parent body, and the knots would also probably possess rotations. In addition to the knots there would be a general scattering of the larger part of the mass in irregular nebulous clouds.

Development of the Nebula into the Solar System. — It remains to be seen how the nebula resulting from tidal disruption can become the embryo of an orderly planetary system. If the matter were shot out from great depths in the sun by its normal expansive forces plus the tidal forces, the velocity of departure might rise high above the observed velocities of 300 miles per second. If

400 miles or more it would be above the " critical velocity " of the sun. The gravitative attraction of the latter could then never reclaim that matter, because the decrease in the outward velocity due to the solar attraction would never bring the velocity down to zero and could therefore never reverse the motion of the escaping matter, and bring it back to the sun.

It is doubtful if the sun could have drawn back to itself material expelled with a velocity of even 300 miles per second, for the passing star, by lowering the gravitative power of the sun on the line passing through the two, would temporarily decrease on that line the critical velocity. In other words, it would help to drag matter away from the sun, even though that matter could not catch up to it, but would be left wandering in interstellar space, forming possibly cometary and meteoric material for other systems. But some, or possibly all, of the matter of the exploded sun may have had lesser velocities of escape and would consequently remain within its gravitative control. In so far as it was not deflected sideways by some extraneous force it would fall back on the surface of the parent as the water of a geyser falls back into its pool. But the gravitative pull of the passing star would serve as such an extraneous force, analogous to the wind which blows part of the geyser water, as it rises and falls, to one side of the basin. The matter shot out toward the passing star would be attracted sideways after it as the star receded into space. On falling back toward the sun it would consequently pass to one side and elliptical orbits of the separate particles would become established. The material shot out in the reverse direction, from the opposite side of the sun, would meet much the same conditions except that the sidewise pull of the passing star would be less on it than on the sun. It is seen that the lateral or deflecting force acting on both arms of the nebula would be due to the difference between the pull of the passing star on the arm and on the central body. The spiral arms do not then represent the path along which the material was shot out, but mark the rotation around the central body or sun, both of the axis of expulsion during the passing of the star and of the matter after it is expelled.

The spiral nebula would be developed in a plane (Fig. 340). That plane is established by the hyperbolic orbit of the passing star with the sun at the focus of the orbit. The new system would thus show in its nature features imposed by both its parents.

The correspondence in form of the innumerable spiral nebulæ hidden in the heavens but revealed by the telescope with the ex-

pectations as given by mathematical analysis is what gives strength to the conclusion that they are in fact the result of such tidal disruption as here outlined, acting upon gaseous bodies.

Origin of the Planets

Development of Planets from Spiral Nebulæ. — From such a nebulous fiery birth Moulton especially has shown how, in accordance with the laws of celestial mechanics, a planetary system could result.

The matter which has converged into the planets would be that residue of the solar tidal disruption which did not pass beyond gravitative control and did not fall back into the body of the sun. This residue is only a very small fraction of the sun's mass. It would appear probable, however, that the solar disruption was very great in order to give an axial revolution to the reaggregated matter forming the present sun, so that its equator should be, as observed, only seven degrees from the mean plane of all of the planetary orbits. The present revolution of the sun is probably due then to the whirl produced during tidal disruption and not to an axial rotation belonging to the sun before the event took place.

This brings us to the final stage in the evolution of the planets according to the planetesimal hypothesis (see Figs. 339–341). In the arms of the spiral nebula were knots or nuclei of matter constituting the cores of the planets. Four small knots, the earth-moon knot being a double one, represented the beginnings of the four small inner planets (see table, page 516). In the zone of the planetoids there was, however, no dominating nucleus, and they have therefore remained to this day largely in the planetesimal state. Four greater nuclei beyond were the beginnings of the major planets. Smaller nuclei associated with the larger marked the presence of satellites.

The orbits of the planetary nuclei and of the scattered planetesimal swarm were highly eccentric, having the form of a tangle of ellipses of all forms and sizes but lying in nearly a common plane and with a common direction of revolution about the central body. Collisions would inevitably occur at the crossing of the paths in the course of numberless revolutions and the nuclei would have sufficient mass and consequent gravitative power to retain the matter colliding with them. In this way, each planet would in the course of time clear up an orbital zone, and these zones, because of the eccentricities of the orbits of the component particles, overlapped each other with the exception of a region between Mars

and Jupiter. But Moulton has shown that in such planetary growth by accretion, an axial revolution would arise in the same direction as the orbital revolution, and that the incorporation of all the planetesimals would cause the eccentricities to cancel out, giving to the whole mass a nearly circular instead of a highly elliptical orbit. This would lead us to believe that the original nucleus was but a small part of the completed planet, so that its original ellipticity of orbit was submerged beneath the average influence of the added masses. With this growth of the planet to final form and in orderly relation to the sister planets and the parent sun, geologic history, as distinct from cosmic history, finds its beginnings.

Relations of Earth and Moon. — The moon revolves at a mean distance of 239,000 miles from the center of the earth. It has a diameter of 2160 miles, more than a quarter of the earth's diameter, but owing to a lesser density as well as a smaller volume, its mass is only one eighty-first part of the mass of the earth. Nevertheless, it is larger in relation to its primary (the earth) than any other body in the solar system, so that there is some justification for referring to the earth-moon system as a double planet.

Under the simple terms of the nebular hypothesis the moon was looked upon as made by the coalescence of an equatorial ring of gaseous matter abandoned by the earth when it had a diameter of about half a million miles. The same objections apply, however, to this hypothesis of evolution for the satellite as have been given against the hypothesis of the evolution of the planets under the terms of the nebular hypothesis.

George H. Darwin in 1879 suggested, as a result of his investigations upon the theory of tides, that the earth may have formerly revolved once in about five hours instead of twenty-four. A much greater equatorial bulge, or flattening at the poles, would then have resulted from the high centrifugal force, and this equatorial zone may have been made unstable by the rhythm of the tides produced by the sun. He conceived that one side of the earth's crust may thus have been broken away, as in a bursting flywheel which has revolved at too high a speed. The matter so liberated would begin to revolve around the earth close to it, and, gathering into a body made spherical by self-gravity, would give rise to the moon. Fisher then suggested that the bed of the Pacific Ocean basin might be the scar made by the moon's birth, and the Atlantic Ocean basin the result of that part of the continental crust which forms the Americas breaking away from the main mass represented by the Old World and drifting westward toward the depression left by the disruption. Thus Fisher would account for the formation of the ocean basins as due to the removal of a part of an outer lighter crust which went to form the moon. Darwin showed, as a part of the same problem, that, under certain conditions, the enormous tides raised by the moon in close proximity to the earth would slow down the earth's rotation like a friction brake and react upon the moon by driving it farther away from the earth. This hypothesis of the moon's origin has been widely held. It rests upon sound principles, but there are involved many uncertain factors.

Moulton has more recently reëxamined the whole problem and tested its

probability or improbability in a number of ways. He found that the moon would have had to break away from the earth when the equatorial diameter of the latter was 18,400 miles, and it appears probable that the tides raised by the newborn moon, instead of beginning to drive the moon away, would precipitate it again on the earth. If, however, the moon did get away and tidal retardation began, then the time demanded to push it to its present distance, depending upon a new estimate of tidal friction, would be hundreds or thousands of times longer than those estimates which are given by geologists for the age of the earth.

The conclusion, therefore, is that the moon never was a part of the earth's body, but that earth and moon originated as two companion nuclei in the spiral nebula and approximately at their present distance. The nucleus of the earth must have been, presumably, much more massive from the first in order to bring dominantly to it the planetesimal infall and so result in an even greater disparity of mass. The moon, thus restricted in its growth, has at its surface but one-sixth of the gravitative power of the earth. It has, therefore, never in its history been able to hold to itself either an atmosphere or an ocean. These gaseous emanations as they have been exhaled in connection with the wide-spread igneous activity of the moon have been warmed and expanded by the heat of the sun and then diffused into space. The moon shows a surface, therefore, upon which the gradational forces of air and water have never worked. Even in the expression of its internal activities it differs from the earth, deep-seated contraction with crustal wrinkling appearing always to have been absent. This contrast supports the view that the contraction of the earth is due to the enormous pressures developed by the weight of the outer parts and producing condensation of the nucleus. The fundamental distinctions in character and in history between earth and moon appear, then, to be traceable to the far greater mass of the earth at the end of its growth, and to the dominance of its nucleus even at the beginning of the formative era.

CHAPTER XXVI

PRIMORDIAL GEOLOGIC TIME

We learned in the previous chapter what were the probable cosmic stages which led up to the origin of the earth, as deduced from a study of the heavens guided by mathematical analysis. Then follows possibly the greatest blank in our knowledge.

Absence of Direct Evidence. — The history of the earth is deciphered from the study of its crust, but the oldest known rocks are lava flows and water-laid sediments belonging to the Archeozoic era. The sediments show that even at that time the orderly processes carried on by air and water under the influence of solar heat and light were in operation as in later ages. But these oldest Archeozoic rocks everywhere, so far as now known, float upon and are torn to pieces by younger igneous rocks. These, rising in molten form as granitic magmas, may have everywhere remelted and destroyed the original surface of the earth. Direct geologic study, therefore, can not recover that primordial history which preceded the Archeozoic. Neither can the direct study of the heavens help, for they show by the light of nebulæ only the stages which lead up to planetary birth, not those which follow. There is, then, an uncharted ground between the provinces of Astronomy and Geology, a *Primordial Time*, which, because terrestrial life also found its origin then, may be subdivided into an early lifeless eon, the *Azoic*, and a later one, the *Eozoic*, the eon of the dawn of life.

Dana in 1874 embraced all pre-Paleozoic time under the term Archean, which means ancient, and then divided it into Azoic and Eozoic. The Azoic, he said, "is the era in which the physical conditions were incompatible with the existence of life. But this era so far as now known, is without recognizable records." The name Eozoic was given up in 1895 for Archeozoic, which embraces the oldest known formations.

Our ideas as to the probable nature of events in that time of which we have no record are controlled by our conceptions of the nature of the preceding and succeeding eras. Our knowledge of these has increased greatly during the past generation and has accordingly profoundly modified many ideas once widely held concerning the formative stages of the earth.

Stages under the Laplacian Hypothesis

These older views were in part the direct outgrowth of the Laplacian or nebular hypothesis, in part the results of interpretations made in the early days of geologic science regarding various features in the outer structure of the earth. The stages of the earth's early history, as conceived by Dana and widely accepted until very recently, were as follows:

(1) **Astral Eon.** — The nebulous equatorial ring liberated by the primordial sun broke into parts, as described in a previous chapter, and gathered into a spheroid containing the mass of the earth and moon. As it condensed it grew hotter and for a long time shone like a star, hence the idea of an astral eon. It passed from a gaseous into a fluid globe surrounded by a heavy vaporous envelope containing the future water of the earth, or the dissociated elements thereof, and other heavy vapors or gases. It is postulated that during the early part of this eon the earth also gave rise to an equatorial ring that finally coalesced into the moon.

(2) **Azoic Eon.** — The time without life, as this eon is called, is divisible into two eras, as follows:

(*a*) *Lithic Era.* — The earlier portion of the Azoic eon is known as the lithic era, because the earth's surface was then all rock and the globe was still very hot, although there was a solid rocky crust, the *original crust*, wholly crystalline in structure, with a temperature at the beginning above 2500° F. The atmosphere still contained all of the water of the globe, all of the carbonic acid since locked up in limestone and that corresponding to the carbon now in carbonaceous and organic substances, and all of the oxygen since shut up in the rocks by oxidation, as well as that of the atmosphere and of organic tissues. As the earth shrank, due to cooling, lateral pressure and crustal disturbances were introduced.

(*b*) *Oceanic Era.* —At the beginning of this era the waters were condensed into an ocean universal over the earth, or gathered in oceanic depressions, with finally some emerging lands, the temperature at the surface of the earth being perhaps about 500° F. Tidal action now set in, and because of the friction thus engendered, the retardation of the earth's rotation began. Oceanic waves and currents and embryo rivers commenced their work about the emerged and emerging lands; the large excess of carbonic acid and oxygen in the air and water became a source of rock destruction. Before the close of the era, there arose the formation of limestones and iron carbonates by chemical methods, removing carbonic acid from the

air and so commencing its purification. Sediments accumulated for the first time without immediate metamorphism, and in these originated the earth's *super-crust.*

(3) **Eozoic Eon.** — Life now appeared in its lowest forms. This eon is also divided into eras, (*c*) *the era of first plant life,* and (*d*) *the era of first animal life.*

Objections to the Older Views

Absence of an Original Crust. — It has already been stated that the fundamental granite gneisses which underlie all other rocks contain evidence that they were upwellings in molten form and younger than some metamorphosed sedimentary rocks which they envelop. The view that these granitoid rocks constituted an original crust must then be abandoned. The gneisses which form the foundation rocks do not give any direct information as to the nature of the original crust and can at present hardly be used as a convincing argument either for or against the nebular or planetesimal modes of earth origin.

Theoretic Original Atmosphere. — The atmosphere of the Azoic eon was assumed, as we have seen, to have been very thick and dense, and it was thought that out of it was gradually condensed all of the water of the globe and most of the carbonic acid and the oxygen now locked up in the rocks. Not so long ago geologists also held that vast quantities of carbonic acid still remained in the atmosphere in Carboniferous times, and that accordingly the denser atmospheric blanket was retaining more of the sun's heat then than it has retained since that time. If this were the case, the climate of the earth should have been very warm and equable throughout its earlier history, and this belief was adhered to even after the glacial climate of the Permian was discerned; but when the much older ones of Proterozoic time were discovered, it became clearer that the climates of the geologic ages have been very much alike, that is, warm mild climates continuing for very long times, separated from one another by cooler to cold climates of short duration.

In this matter the testimony of the organic remains is equally as decisive as is the physical evidence of the glacial climates. The plants and animals of the seas and lands as far back in geologic time as the Cambrian all show in their physiological functions and adaptations that their environments were very much alike, alternating between warmer and cooler. But at the close of the eras appear times of stress and great organic destruction, along with rapid evolution, and this evidence is now seen to fall in with marked

changes in the environment, and often with glacial climates. Accordingly, there is little evidence to show that the climates since the beginning of the Proterozoic were as postulated by the older geologists in accordance with the nebular hypothesis of Laplace.

Primitive Water of the Atmosphere. — It was also held that not only was all the water on the surface of the earth suspended in the atmosphere when the earth was in the fluid state, but also all that which has since soaked deeply into the rocks. If this were true, the oceans must have been larger and there must have been more water at the surface in the earlier part of the Azoic eon than at any time since then. A study of the animal life of the present deep seas, however, gives testimony that the oceans have become deeper with time and especially since the Paleozoic era. Further, the study of volcanic emanations shows that great quantities of water are extruded by them and by the thermal springs. The older geologists said this was the percolating water returned to the surface of the earth (the old or "vadose water"), but the newer geology holds quite differently, that it is new water ("juvenile water"), freed out of the magmas deep within the earth's crust. Not only this, but the volcanoes are also liberating great quantities of carbon dioxide and constantly replenishing the atmosphere and oceans with that taken out of them and stored in the accumulating rocks.

We therefore again see that this older view fares no better with its explanation as to the origin of the earth than it does with the origin of the solar system. For these reasons astronomers, physicists, and geologists have been seeking for a better hypothesis that will explain the origin of the earth in accordance with the known facts. In this connection we need now consider but one other theory, — the planetesimal origin of the earth as propounded by Chamberlin and Moulton.

Stages under the Planetesimal Hypothesis

According to Chamberlin, there are *six stages* in the Azoic (4) and Eozoic (2) history of the earth before we come to the earliest of geologic times, all subsequent time being embraced in the seventh or "gradational stage." These stages, slightly rearranged, are defined as follows:

(1) **Nuclear Stage.** — The earth started in a spiral nebula, with the nebular knot acting as a nucleus, and increased by gradual condensation as planetesimals were gathered into it, until it became a small planet which continued to grow by the capture of more planetesimals. The diameter may have been between 2000 and

3000 miles. At first the discrete matter of the nucleus was held together by mutual gravity, and later the whole passed gradually into a solid mass.

(2) **Initial Volcanic Stage.** — Before the earth grew to any large part of its present mass, the self-compression which arose from its own gravity, when at a diameter of about 2000 to 3000 miles, is thought to have produced sufficient internal heat to have reached the melting points of the common kinds of rock under low pressures, and as this heat crept outward, it would reach rocks at pressures that would permit liquefaction. Moreover, as has been said above, as soon as volcanic action was established it is believed to have made notable contributions of gas to the atmosphere.

The internal heat may in part have been produced by the infall of planetesimals, and an unknown amount was probably inherited from the nebular knot that constituted the original earth-nucleus. The chief source of internal heat is, however, assigned to the progressive interior condensation of the growing body as planetesimals were added to its surface. Another source of heat lay in the atomic and molecular rearrangement of the growing nucleus. The highest temperature must have been at the center, diminishing toward the surface.

(3) **Initial Atmospheric Stage.** — There may have been a stage after the nucleus was condensed during which the earth was too small in mass and consequently too weak in gravitative power to hold to its surface the gases of an atmosphere, but if the earth then had a mass at least one tenth of that which it has at present, it probably had a limited atmosphere like that of Mars, gravity then overcoming the tendency of the gas to diffuse into space. If it was much smaller than this, it probably had little or no atmosphere. The moon has none because of its small mass, which is but one eighty-first of that of the earth. As the earth grew larger, atmospheric molecules were gathered to it, and sooner or later it gained the power to hold them, and accumulated an atmosphere. Later on, as volcanic action set in, the occluded and condensed gases of the rock material were given out and were added to the atmosphere. These gases of the interior nucleus were hydrogen, carbon dioxide, and carbon monoxide in leading amounts, and marsh-gas and nitrogen in small quantities; in the atmosphere they occur chiefly as water-vapor, carbon dioxide, and nitrogen. With such an atmosphere also goes the possibility of standing bodies of water, and in this atmosphere and hydrosphere lie the necessary materials and environment for the origination of life in its lowest forms.

Just what the temperature may then have been is unknown, and it is possible that it was not yet favorable for life. It may have been that life began at this early time; if not, it certainly became possible long before the earth attained its full growth through accretion.

(4) **Initial Hydrospheric Stage.** — Water in the form of gas is light and active, and may at first have escaped; but when the earth had attained sufficient size, water vapor was held in the atmosphere, and when, at length, the point of saturation was reached, it took the liquid form and initiated the hydrosphere, which, however, had its inception in the third stage. We have seen that the source of the water, according to the hypothesis, was the same as that of the atmospheric gases.

According to Chamberlin, it is probable that as the planetesimals were gathering upon the small earth they did so irregularly geographically, thus producing an uneven surface. Accordingly, when the water accumulated upon this surface, it gathered in these accidental depressions, making innumerable small bodies of fresh water. These bodies of water initiated *the origin of the oceans.* The planetesimal material which afterwards fell into these lakes was protected from weathering, while the material that fell on the protuberant areas was exposed to weathering and leaching, leaving behind siliceous residues, with an attendant lessening of specific gravity. Thus the depressed areas tended toward potentially higher specific gravities, and hence toward still further depression when deforming stresses were brought to bear on them, while the elevated areas tended to grow relatively lighter and more protuberant under the stress of deformative movements. Therefore, the differentiation of the oceanic basins from the continental protuberances began almost as soon as the hydrosphere started to gather, which was long before the earth had reached its present size, and has continued to the present time.

This evolution is of fundamental geologic importance, for it involves the origin of the ocean basins and of the continental platforms, and these constitute at once the grand topographic features of the globe, the great units of deformation, and the controlling physical factors in the evolution of life. It is assumed that this evolution began when the earth had attained the size of Mars, which has a diameter of about 4200 miles, for it then began to be able to retain water vapor in its atmosphere and consequently oceans upon its surface. The subsequent growth of the earth, therefore, formed a shell about 1900 miles thick, and it is within this shell that the physical evolution of the oceans and continents has taken place.

Modified Theories of the Hydrospheric Stage, by Professor Barrell

This series of events, as outlined by Chamberlin, is a logical outgrowth of the planetesimal hypothesis, but that hypothesis is, of course, sufficiently elastic to accommodate itself to many possible modifications. This view of the origin of continents and ocean basins, for example, depends upon a sub-hypothesis of differential weathering proceeding effectively and dominating the surface processes from that stage when the growing earth could, by virtue of its increasing gravitative power, first begin to hold water to its surface in liquid and gaseous form. We may, however, consider the contrary postulates that erosion and weathering may not have been effective in this way or that planetesimal infall proceeded so much faster than weathering and erosion as to make the latter processes wholly subordinate in determining the nature of the outer shells. Under such a postulate, the origin of continents and of ocean basins would have to be sought in other causes. There is some evidence which suggests that this alternative sub-hypothesis may be nearer the truth than the one whose consequences have been described in detail.

Three Hypotheses as to the Nature of the Earth's Interior. — As to the nature of the earth's deep interior but little is positively proved. That little may be summed up in the statement that it is very dense and very rigid. Beyond this, our conclusions must be guided by probabilities as suggested by hypotheses which are in accord with known natural phenomena and known natural laws. As to the chemical composition of the earth's body, three views which have been entertained are worthy of mention.

(1) *Interior of Metallic Iron.* — First, it has been thought probable by many that the core of the earth for some 6000 miles in diameter is of metallic iron. This in turn is surrounded by a rock envelope which in the deeper parts is thought to be very basic, that is, high in content of basic elements represented by iron or other metals, low in the acidic element, silicon. Such rocks are the dark and heavy basalts and gabbros. Toward the surface it is thought, according to this view, that the lighter and more siliceous rocks prevail, marked by the presence of quartz. The typical example of such rocks is granite. It is thus assumed that the increase in density in the earth is essentially due to progressive changes in chemical composition. The usual explanation of the origin of such a stratification of elements is to assume that the earth was once thinly molten throughout, during which stage a liquation took place analogous to the separation of the slag upon the surface of the molten iron in the reservoir of the blast furnace. There is really no evidence of such an arrangement, and it is difficult to see how, under it, the earth could later solidify throughout. This view is largely an inheritance from the Laplacian hypothesis, and, furthermore, neglects as unimportant the condensing effect of pressure.

It is known that pressure increases with depth to a maximum of about 45,000,000 pounds per square inch at the earth's center. Such pressures are vastly beyond the reach of laboratory experiments, so that their effects in compressing rocks are not known. Matter becomes more incompressible as it is condensed and probably reaches an ultimate limit. This and the central heat are, in fact, all which prevent the rocks from being squeezed into a minute fraction of their volume as seen at the surface of the earth. It is possible, though perhaps not probable, that rocks may be compressed at the center to a third or perhaps a quarter of the volume which they possess when free from pressure. The planetesimal hypothesis suggests as most probable that the earth throughout is of the

nature of igneous rocks but has been solid and rigid from the time of its origin, save for the generation of magmas. The distribution of densities so far as known is in better harmony with this view of the earth's interior than with the view which neglects the great influence of compression and assumes the existence of a central iron sphere. On the other hand, there are some indications given by experiments at very high pressures, that the more rigid bodies, like rock and metals, may not be compressible to one half of their ordinary bulk. The evidence has been interpreted, however, in opposite ways by different physicists, and a positive conclusion has not yet been reached. The composition of the earth's central portions is, therefore, an open question.

(2) *Interior more nearly like Basalt.* — But if the earth consists of silicate rocks throughout, are these basic, intermediate, or acidic in composition?

The study of igneous rocks has led many to believe that at the initiation of a period of vulcanism the great reservoirs of magma have a basic or intermediate composition. The granites are a later differentiation product, separating like cream from milk, and rising, by virtue of their lesser density, to the higher parts of the reservoirs. This brings us to the second view of the chemical nature of the earth's interior — that the average composition probably approaches throughout to that of basalt rather than to that of metallic iron on the one hand, or granite on the other.

We are prepared now to consider the supposition of the influence of weathering upon such an earth during the outer 1000 or 2000 miles of its growth. It is not clear that it would result in such a lateral segregation of densities as to build, on the one hand, denser and therefore depressed oceanic crustal segments, and, on the other, lighter and therefore elevated continental areas.

In the first place, free oxygen could hardly exist in the atmosphere in contact with such wide-spread basic rocks as more than a trace, since the large amount of ferrous iron and sulphur of these rocks would rapidly consume such oxygen as existed. In the second place, there would be little or no quartz to make sand residues as a result of weathering and erosion, and the great amount of ferric oxide going with the clay would prevent this from being a lighter part of the weathered products. There are other difficulties in accounting for the origin of ocean basins and continental platforms in this way, but they are also involved in the third view, which may now be considered.

(3) *Interior more nearly like Granite.* — Assume, as a possible alternative supposition, that the average composition of the infalling planetesimals was of the nature of granite, or that igneous activity during the later growth stages of the earth kept separating granites as surface rocks. Then chemical weathering would tend to separate the insoluble siliceous portions, chiefly quartz and clay, from the metallic portions, the metals forming soluble bicarbonates, sulphates, and chlorides. This would have resulted in a rapid saturation of the gathering ocean waters by the very soluble salts of sodium and potassium. The excess of these salts would thenceforward have to be deposited, and the ocean would continue to exist in a saturated state. But the present oceans are very far from being saturated. The waters of the Dead Sea, for instance, hold from 20 to 25 per cent of salts, whereas the ocean water holds but 3.3 to 3.7 per cent. This oceanic content corresponds to the weathering and erosion of a layer of igneous rock only about half a mile thick if spread over the globe, or less than 2 miles if derived from the continental areas. The lack of more salt in the sea can not be ascribed to the elimination, in the form of salt, of deposits from waters of the present salinity, for all those known comprise but an insignificant fraction of the salt which is in

solution, and the processes of abstraction are inadequate to account for such a hypothetical early precipitation. If the ocean had once been saturated, there is no means known by which its salinity could be so decreased save by dilution with fresh juvenile water from the depths of the earth. This would force us to believe, therefore, either that planetesimal infall until its latest stages was so rapid as to render negligible the influence of weathering, or that the greater part, probably eight or nine tenths, of the ocean water was liberated by the igneous activity of the Archeozoic and later eras. The first of these two suppositions seems more probable, but both may in a measure be true.

It is, moreover, not clear, even if weathering of granitic rocks did go on accompanying planetesimal infall, that any such distinction in relief would arise as now separates continents and oceans. The calcium, iron, and magnesium carbonates are heavier, it is true, but the alkaline chlorides are lighter than the siliceous sands. The soluble salts, furthermore, show tendencies to be precipitated in shallow waters rather than on the bottoms of ocean basins.

As another suggestive line of evidence, igneous activity brings up samples of earth substance from a great depth, and those erupted in oceanic islands show a higher average specific gravity than those erupted from volcanoes on the continents. But the differences in composition show that soda and potash tend to segregate with silica. This is not the kind of separation which would go forward as a result of *weathering;* rather is it the kind of difference which is found to arise by a liquation or separation of molten magmas into lighter and heavier portions analogous to the liquation of an emulsion of oil and water.

It seems probable, furthermore, that considerable tracts of continental lands have, in the course of later geologic time, broken down and added their areas to the ocean basins. The development of the latter can, then, not be wholly ascribed to causes operating only during the earth's formative eon. Changes in density, effected possibly by broad igneous activity, may be a more important cause, resulting in progressive subsidence of the heavier sections of the crust.

Conclusions as to the Nature of Earth Growth. — The best conclusion with present knowledge seems, therefore, to be that planetesimal infall dominated the activities on the earth's surface until its complete growth had been nearly attained. This may be due to a relatively great rapidity of infall, or to weakness of erosion and sedimentation in that formative eon, owing to a thin primal atmosphere, a meager ocean, or an ineffective warming of the earth's exterior.

(5) **Initial Life Stage of Eozoic Time.** — Suitable conditions for life did not exist until after some notable development of the atmosphere and the hydrosphere, but, as these were gathered about the earth at an early stage, it is possible that some forms of life began long before the earth was full-grown. The necessary conditions for life may have obtained when the earth nucleus was the size of Mars. Under the planetesimal hypothesis, therefore, the time during which life may have existed on the earth is very much longer than that assumed under the older hypotheses.

Hypotheses as to the Origin of Life upon the Earth, by Professor Barrell

H. E. Richter in 1865 advanced the speculation that living germs might be eternal, pervading all space. This is the hypothesis of "cosmic pangenesis."

Arrhenius (1908) raised the speculation of cosmic pangenesis to the dignity of an hypothesis, holding that the pressure of light was able to drive germs from the outer atmospheres of planets, distributing them through the depths of interstellar space. He holds that the absence of an atmosphere and the cold of space would indefinitely suspend the life of germs without destroying their vitality. The spores or germs would be swept outward with increasing velocity until, on wandering into the neighborhood of other stars, the light pressure of the latter would tend to arrest their meteoric speed and eventually turn them away on another interstellar journey. While in the state of arrested flight, however, they could be attracted to or come into contact with planets of the visited system. Most of the germs would be burned like meteors by frictional impact at high speed against the planet's atmosphere. In those cases, however, where the germ overtakes or is overtaken by the planet it might enter the atmosphere at low velocity and thus be enabled to seed the planet with life.

This hypothesis does not pretend to solve the ultimate origin of life, but only the origin of life upon the earth. It puts off the ultimate origin of living protoplasm as another problem, perhaps insoluble. Under its terms it is to be expected that any planet may develop life whenever its surface conditions offer the necessary environment of atmosphere and warmth.

Chamberlin, however, considers it highly improbable that the vast and empty interstellar spaces should be sufficiently seeded with spores to afford that rare chance of a germ encountering and successfully entering the atmosphere of a planet in another system without having its vitality destroyed, and it must further be remembered that even the possibility of the escape of spores from a planetary atmosphere can not in the nature of things be regarded as demonstrated. Chamberlin considers it more probable that life originated on the earth independently of other planetary bodies. Organic chemistry has not yet shown how living protoplasm could be organized without the presence of antecedent living protoplasm, but Chamberlin thinks that the necessary conditions may have arisen during the infall of planetesimals and after the development of the primitive atmosphere and ocean. The porous crust would have offered a great variety of chemical and physical conditions. Gas-laden, permeating waters in the presence of warmth and in a porous medium may have built up here and there colloidal substances capable, by catalytic action, of carrying forward the construction of complex molecules from carbon with other elements. The earth being as yet sterile, this primordial protoplasm would not have become attacked by carnivorous germs and would thus have had opportunity to evolve into that efficient chemical and physical form wherein it could continue its own existence.

It is seen from these sketches of possible modes that all hypotheses regarding the origin of terrestrial life are, in the present state of knowledge, highly speculative. Until there is accumulated a larger basis of significant data, the problem can hardly be regarded as within the domain of science.

Under either view which has been given, it seems that life may have arisen on the earth long before the latter had attained its full growth and present diameter. With the introduction of plants and animals there came into action through their physiological activities all of the great factors potential in the earth's physical evolution, ready to dominate the geologic activities of the surface as soon as the formative era was ended.

(6) **Last Stage of Planetesimal Accretion.** — During all the previous stages the earth was growing larger through the gathering in of the planetesimals. It is probable that the accretion was rapid at first, causing the diameter of the earth to increase more rapidly. Finally, the time came when practically all of the planetesimals of the original nebula under the influence of the attraction of the earth and the moon had been gathered. The earth probably had a greater equatorial diameter then than now (7918 miles), but how much shrinkage has taken place since is not yet known.

Some internal heat may have been retained by the nebular knot or nucleus, and it is thought that this initial heat increased with the growth of the mass. The maximum of heat may have been attained after the earth had arrived at bodily maturity, due to the increased compression of increased mass, supplemented by heat of chemical and radio-active origin. With the increase of internal heat came the rise of volcanic activity, and it has continued intermittently ever since. During long times the rising of this heat may not have been very active, but periodically it became great, and these periods of marked vulcanicity seem to fall in with the times when the earth is undergoing either regional (orogenic) or general (epeirogenic) mass movements, due to shrinkage that is brought about by internal condensation, not so much by loss of heat as by increase of density due to atomic or molecular internal alterations in response to the pressures generated by gravity.

What this internal heat was then or is now no one knows. However, it has been stated in the first part of this book that a temperature of at least 2000° C. (3600° F.) may be reasonably assumed to exist in the region of the source of some of the volcanic lavas.

(7) **Gradational Stage.** — After the growth of the earth had ceased, the surface was no longer subject to continual burial, but was exposed ever afterward to the action of air and water, and heat and cold. The material removed by these agents from the higher parts was deposited at lower levels and in the main in the oceanic basins and their continental overlaps. The seventh stage, therefore, embraces all subsequent geologic time, and its dominant process was gradational. Vulcanism and diastrophism were other active geologic processes, of slight import throughout long ages, but of marked character during the short intervals which divide geologic history into the periods and eras of time.

CHAPTER XXVII

THE ARCHEOZOIC ERA

History of Classifications

The greater part of Canada, or, rather, the Canadian Shield, of over 2,000,000 square miles in extent, exposes the oldest portion of the North American continent (see Figs. 348 and 365). Here lies the very complex record of event upon event, made during the earlier eons of geologic time.

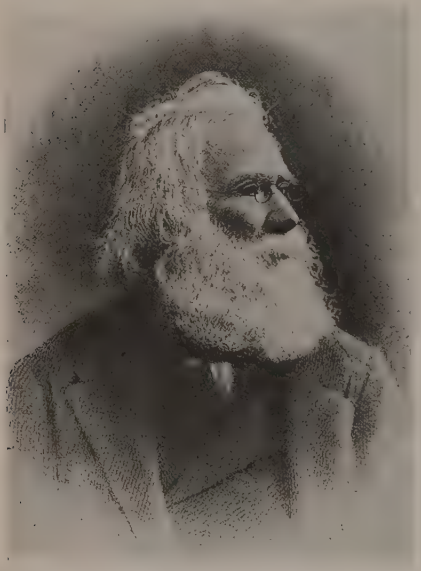


Fig. 347. — Sir William Logan (1798–1875). Father of Canadian geology and author of Laurentian and Huronian.

Work of Sir William Logan. — The beginning of the unraveling of this history fell to William Edmond Logan (1798–1875), the first director of the Geological Survey of Canada. He did his work well, and, as he inaugurated the detailed study of pre-Cambrian formations, he has been called the Father of Pre-Cambrian Geology.

Geikie says of Sir William Logan: "At the very beginning of his connection with the Geological Survey of Canada in 1843, Logan confirmed the observation [of previous geologists] that the oldest fossiliferous formations of North America lie unconformably on a vast series of gneisses and other crystalline rocks, to which he continued at first to apply the old term Primary. By degrees, as he saw more evidence of parallel structures in these masses, he thought that they were probably altered sediments, and he referred to them as Metamorphic." After years of labor on the part of himself and his associates, "he proposed for these most ancient mineral

masses the general appellation of Laurentian, from their development among the Laurentide mountains. . . . In the course of his progress, he came upon a series of hard slates and conglomerates, containing pebbles and boulders of the gneiss, and evidently of more recent origin, yet nowhere, so far as he could see, separable by an undoubted unconformability. These rocks, being extensively displayed along the northern shores of Lake Huron, he named Huronian. He afterwards described a second series of copper-bearing rocks lying unconformably on the Huronian rocks of Lake Superior. He thus recognized the existence of at least three vast systems older than the oldest fossiliferous formations. . . .

"Subsequent investigation has shown the structure of the regions which he explored to be even more complicated and difficult than he believed it to be. . . . But he will ever stand forward as one of the pioneers of geology, who in the face of incredible difficulties, first opened the way toward a comprehension of the oldest rocks of the crust of the earth."

Work of the International Committee of 1905. — In 1905 a committee of geologists was appointed by the governments of Canada and the United States to agree upon a sequence of formations and a nomenclature for the pre-Cambrian rocks of the Lake Superior region, the best known area of these ancient formations in North America. The report of this International Committee was a great advance upon the older classifications still seen in text-books, and it may have seemed to some at that time to have fixed the larger divisions, leaving for future work only the development of details. However, our knowledge of these rocks has since grown with leaps and bounds, and the question of another revision was taken up by the Twelfth International Geological Congress in the summer of 1913. At least four somewhat different classifications were there offered, and while the table presented in Chapter XX follows in the main the one of Coleman, yet the views of Leith, Adams, Lawson, Collins, Miller, and Knight have also been considered. It is, however, a foregone conclusion that this classification, like those preceding it, is by no means final.

Method of Correlation. — In deciphering the pre-Cambrian chronology the geologist has no fossils to depend upon, and the criteria used in the working out of the geologic sequence are: (1) similarity of rock character, (2) structural nature of the rocks, (3) superposition of the formations, (4) crustal movements, and (5) cycles of erosion. In order that these various phenomena may be fully evaluated in a time table, it has become necessary to in-

clude in the table the periods of deformation and the times of wide-spread erosion, and to give names to them as well. The incorporation of these principles is a feature of the pre-Cambrian table presented on pages 444 and 445, which in the main follows the scheme offered by Barrell in 1914. Periods of igneous invasion and crustal revolution are shown on the right, and periods of sedimentary record on the left. The shorter erosion intervals indicating the breaks which separate periods are shown by narrow spaces, while the great named intervals are brought out by wide spaces. Even this magnification, Barrell thinks, minimizes the long duration of the great erosion intervals. The result, however, serves to make prominent the two most significant and distinctive features of the pre-Cambrian: (1) the wide-spread crustal revolutions, characterized by vast upwellings of molten rocks; and (2) the profound depth to which erosion has planed, revealing over great areas the former levels of the crust which, while deeply buried, were subjected to regional metamorphism — levels whose original place was miles beneath the present surface.

Length of Pre-Cambrian Time. — It is generally admitted by geologists that the time back of the Cambrian, the first period with an abundance of fossils, was extremely long. Coleman says of it: " At present no part of the earth's history is attracting more attention than the pre-Cambrian, and we are gradually disentangling obscure relationships and opening out a wonderful vista into the past which has already doubled the length of geological time, and bids fair to make the post-Cambrian record only an appendage to the far more important pre-Cambrian story of the world."

Terminology. — In regard to the use of the names *Archeozoic* and *Proterozoic*, for the Age of Unicellular Life, and the Age of Primitive Marine Invertebrates, respectively, the following should be stated. As the post-Proterozoic eras are marked by an abundance of life preserved as fossils, it is highly desirable to bring out this fact in the names through the ending *zoic*, which means life. In the pre-Cambrian eras, however, fossils are exceedingly scarce and a classification of the formations on this basis cannot be developed, yet it is established that life existed throughout the Proterozoic and in all probability the Archeozoic as well. Therefore, the usage of *zoic* in these names is also desirable and harmonizes them with those used for the later ages, even though the classification of the rocks in the older eras is by geologic structure rather than by fossils. Because no direct and accepted evidence of life has been found in

the Archeozoic era some geologists prefer to call it *Archean* (means very old), a non-committal term once applied to all pre-Cambrian formations. *Azoic* (without life) and *Eozoic* (dawn life) are other terms which have been used, but in this book Archeozoic is preferred because it means oldest or primal life, a significance in harmony with our present conception.

Divisions of Archeozoic Time. — In Chapter XX, the geologic events of Archeozoic time are given in tabular form and in relation to the younger formations; below, only the more important events are listed, arranged from younger above to older below:

Table of Archeozoic Events

Erosion record	Ep-Archeozoic interval of profound erosion	
Diastrophic record	Laurentian Revolution, mountain building, and first intrusion of Laurentian granites	
Formation record	Keewatin series	Grenville series of calcareous sediments, mainly younger than Keewatin
	Coutchiching formation	
	Unrecoverable beginning of earth history	
	Cosmic history	

Record of Archeozoic Formations

In Chapter XXVI were described the events that are thought to have taken place during Cosmic time, and, as the earliest geologic conditions preceding the Archeozoic era are unknown, we will proceed to a presentation of the oldest formations known to geologists. For the distribution of the Archeozoic formations see map, Fig. 348.

Basement Complex. — The most ancient rocks at the surface of the earth are often referred to as the "Basement Complex," because they are at the base of the known geologic sequence, and because their internal nature and structural characters are usually so altered and complex that their unraveling has given rise to great perplexity among geologists.

General Characters. — The formations so far determined in the Lake Superior country are the Coutchiching and Keewatin, and farther east the Grenville series of sedimentaries and volcanics; all of these have usually been so repeatedly invaded by intrusions of the dominant Laurentian pink granites that they have been altered completely and their original characters greatly obscured (see Fig. 352). So prevalent are the Laurentian granitic rocks that they cover more than 90 per cent of the Lake Superior country, and for a long time, therefore, they were regarded as the original

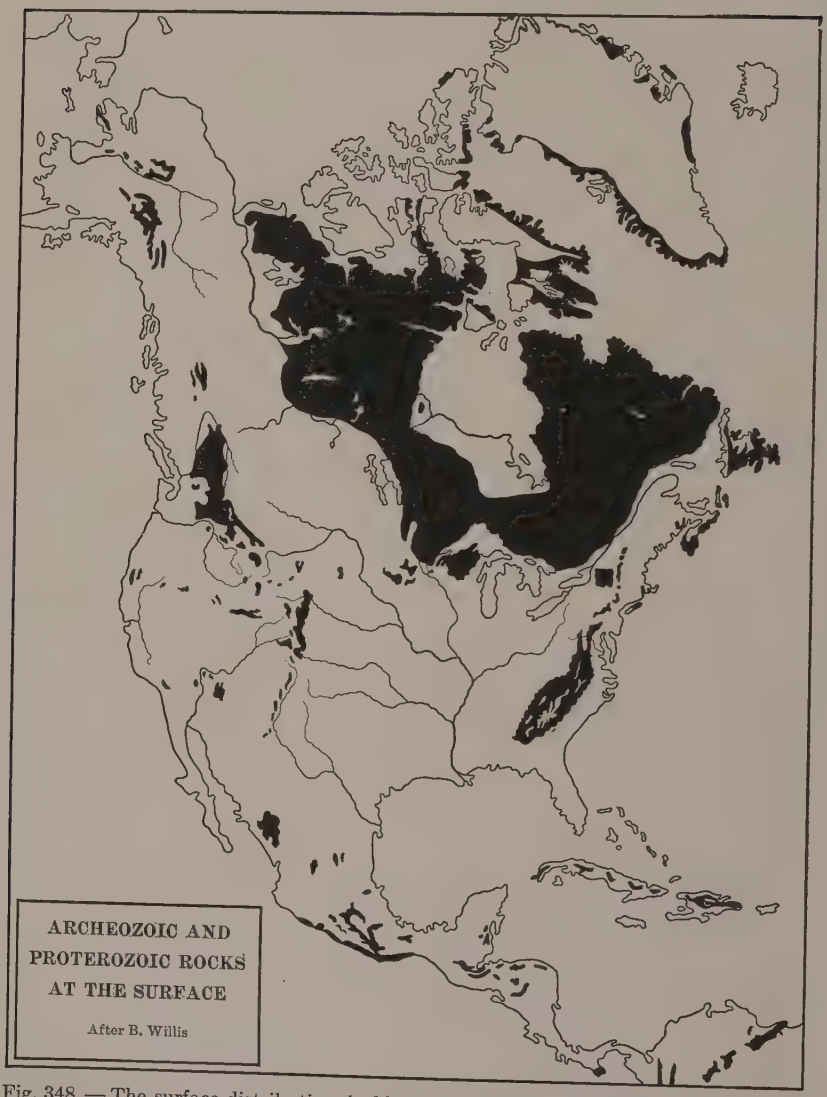


Fig. 348. — The surface distribution, in black, of the undifferentiated Archeozoic and Proterozoic formations. B. Willis, U. S. Geol. Surv. Also see the Geological Map of North America at the end of this book.

cooled surface, or crust of the earth, upon which the above-mentioned formations rested. During the last decade, however, it has become clear that these granites are not older than the formations they seem to underlie, but that they are really younger, for they have upwelled from unknown depths of the earth, have broken up the older rocks, and shattered and invaded the formations above them. In this invasion and injection of the older rocks they have absorbed the material of the latter into themselves and forced their own emanations into the rocks enveloping them. Geologists, therefore, do not as yet know upon what foundation these older invaded formations lie, and it has been said that they "rest upon nothing." Although, from the standpoint of their origin, they do rest upon nothing known, in actual superposition they rest or float upon the younger Laurentian granites. Hence it should not be forgotten by the student that these basement granites are intrusives and younger in their genesis than the Coutchiching, Keewatin, and Grenville series, which rest upon them.

The Archeozoic formations have been described by Van Hise and Leith as a crystalline "complex of basic and acidic [that is, ferromagnesian and feldspathic] surface and deep-seated igneous rocks, of schists and gneisses in part derived from them and in part of unknown origin, and of shreds and small masses of metamorphosed sediments, all unconformably below and older" than the Proterozoic sedimentary rocks. "The sedimentary rocks include slate, graywacke, conglomerate, tuffs, iron formation and marble." The Archeozoic, as a whole, is homogeneous in its heterogeneity, that is, it is alike in its extraordinary complexity. "Its characteristic, though not universal, structure is cleavage or schistosity, often much folded and contorted. It frequently possesses also a banded structure, sometimes developed with the cleavage during rock flowage and sometimes due to minute parallel igneous intrusions parallel to the schistose layers." See Figs. 256 and 259.

The rocks of the Archeozoic include "(1) dominantly plutonic and surface igneous rocks, (2) [usually] small masses of sediments, (3) considerable masses of schists and gneisses clearly derived from secondary alteration of the igneous and sedimentary rocks, (4) very subordinate amounts of gneisses resulting from subcrustal fusion of sediments, and (5) other schists and gneisses of unknown origin."

Geographic Distribution. — Archeozoic formations are known in many countries, but chiefly in North America, Finland, Norway, Sweden, China, and Australia. In North America the greatest

Fig. 349. — Eastward view up the Kaibab, Grand Canyon of the Colorado, Arizona. The horizontal Paleozoic strata (4300 feet thick) rest upon the contorted and peneplained Archeozoic. U. S. Geol. Surv. *V*, Archeozoic (Vishnu schist); *U*, thinned edge of Proterozoic (Unkar); *T*, *BA*, *M*, Cambrian (Tonto); *R*, *Ss*, *Ssh*, *C*, Mississippian and Pennsylvanian.

area is that of the Canadian Shield, with much smaller areas in the Adirondacks of New York and in the highlands of New Jersey and southeastern New York. Similarly metamorphosed rocks, perhaps of the same era, occur in the southern Appalachians. Other exposures are found in the Grand Canyon of the Colorado (Fig. 349) and in the Rocky Mountains (Fig. 348). However, throughout the Cordillera there occur indiscriminately great areas of granite bathyliths, and, while most of these are Mesozoic and Cenozoic intrusions, Lindgren estimates that about 10 per cent of the region is occupied by bathyliths of Archeozoic time, nearly 80 per cent of which consist of granite.

Graphite. — The attention of geologists has long been attracted to the great quantity of graphite in the Archeozoic strata, chiefly in the quartzite-schists. Sir William Dawson long ago said there was more graphite disseminated in the Grenville series than there is carbonaceous matter in the entire Carboniferous (coal-bearing) system. Bastin states that in the Adirondacks the graphite varies from 3 to 10 per cent by weight of the rock. Near Hague, on Lake George, New York, occur alternating layers of graphitic schists from 3 to 13 feet thick, and the appearance is that of a fossil coal-bed. This graphite is believed to have been derived in the main from carbonaceous or bituminous shales, of organic origin, and probably the residuum of primitive marine plants.

The **Coutchiching formation** is the oldest series of sedimentaries known and occurs typically in the Rainy Lake country of Canada north of Minnesota. Its thickness at the very least is 4600 feet, and it originally consisted mainly of carbonaceous shales, now metamorphosed into mica schists and dolomite, both probably of marine origin.

The **Keewatin series** overlies the Coutchiching and consists almost wholly of the most ancient lava flows, basalts, and ash rocks. The lavas flowed in the main over the sea bottom, as is shown by their pillow structures. All of these igneous rocks are now altered into greenstones and green schists. The sedimentary strata are less prevalent and consist of ordinary slates, black slates rich in carbon, and iron-bearing formations, with little of dolomites and limestones. Their combined thickness varies between 6500 and 23,700 feet, of which the greater amount is of igneous origin.

Characteristic of the Upper Keewatin are the banded jasper and iron-ore formations that locally attain to 1500 feet in thickness. The hematite and magnetite ores are interbedded with zones of silica and limestone and all are often underlain by carbonaceous slate, a fact of significance in the genesis of the iron ores, since it suggests the agency of life in their formation, as discussed previously, page 170.

Grenville Series. — In the Province of Ontario north of Lake Ontario and east of Lake Huron occurs a vast succession of essentially calcareous strata. We were first made acquainted with the series by Logan, who gave the rocks their name

from Grenville township, although they are known to cover an area of 83,000 square miles. More recently Adams and Barlow have studied the series in detail and have deciphered its relations to the surrounding granites, confirming the intrusive origin of the latter as announced by Coste in 1886. In a single section these geologists determined the thickness as over 94,000 feet (nearly 18 miles), and more than one-half of it is calcareous. Originally this magnesian limestone and dolomite was fine-grained and blue in color, but it is now altered into a pinkish, coarsely crystalline marble. These marbles occur in thick bands, and with them are associated quartzites that have been changed from sandy sediments. There are also interbedded thick bands of hornblende-schist and rusty-weathering gneiss, the former resulting in part from the igneous invasions, in part from alterations of the calcareous rocks by the molten magmas, while the gneiss is the metamorphosed product of what were originally clay shales. This is not only the thickest series of Archeozoic rocks, but also the greatest single succession of limestones known.

The Grenville limestones have been repeatedly invaded by the Laurentian granites, which have not only metamorphosed them into marbles but have also either burned out their carbon or converted it into graphite, while the remaining iron oxide has given the marble its pink color. Serpentine is also often present and in places affords a distinctly banded concretion-like material, often regarded as the earliest known fossil or *Eozoön*, described on a later page.

Lavas of the Grenville Series. — Miller and Knight have found a succession of lavas at the base of the Grenville series. They correlate these lavas with the Keewatin of the Lake Superior region, and place the Grenville as younger than the Keewatin but older than the Paleolaurentian invasion of granites. It may be questioned, however, if these basal lavas are surely Keewatin. Similar volcanic series recurred more than once in pre-Cambrian time, and in the Lake Superior region the Keewatin is the oldest formation resting on the granites. Bathylithic invasions of granites are normally preceded in an earlier stage of the same cycle of igneous activity by outpourings of basaltic lavas and breccias. The Keewatin lavas and Paleolaurentian granites of Lake Superior may, therefore, be genetically connected, but the granites — regarded as Paleolaurentian — invading the Grenville sediments are so far separated in time from the basic volcanics underlying the vast thickness of the Grenville that these two groups of igneous rocks cannot be genetically related. This, then, makes strong the necessity of reasonably proving the Keewatin age of the pre-Grenville volcanics before the Keewatin or post-Keewatin age of the Grenville can be regarded as established. The problem is seen to be one of the first importance, since it deals with the opening of the knowable geologic history of the North American continent. (Barrell.)

Evidence of Life in the Archeozoic

There is no *direct* evidence of a positive nature as yet to show that fossils occur in strata of Archeozoic time. Long ago, however, Sir William Dawson described from the Grenville limestones *Eozoön canadense*, which means "dawn animal of Canada." For a time many accepted these globular masses, sometimes several feet in diameter, as of organic origin and they have figured in many text-books as such since 1864, though no one successfully showed to

what class of animals they belonged. They certainly are not Protozoa as assumed by Dawson. These masses consist of irregularly alternating thin calcite bands and dark green layers, usually of serpentine, and result from metamorphism of the limestone. They are now regarded as probably of organic origin and are thought to be calcareous depositions made by marine plants (algæ).

The *indirect* evidences of life are found, on the one hand, in the presence of carbon in the sediments in the form of graphite, and on the other, in the oxidation to hematite or magnetite of iron oxide which was originally present in the sediments in the forms of ferrous carbonate or ferrous silicate. At the surface of the earth carbon exists in the form of carbon dioxide, either free in the atmosphere or combined with the metallic oxides as carbonates. Under these surface conditions carbon becomes separated from oxygen so far as known only through the agency of living protoplasm and sunlight. In plant tissues in the presence of the leaf green (chlorophyl), the living protoplasm is able by the energy of light rays to chemically decompose the carbon dioxide absorbed from the atmosphere. The carbon is then built up into starch, the oxygen is exhaled. In so far as complete decay ensues upon the death of the tissues, the carbon recombines with oxygen into carbon dioxide and the organic cycle is completed. To the extent, however, that the organic matter is removed from contact with the air, oxidizing decay is prevented. Distillative destruction sets in instead — the first stages by bacterial action — and a residue of elemental carbon remains in the sediments (see also discussion under peat, page 164). The presence of graphite in Archeozoic sediments is therefore an indirect proof of considerable strength that not only did a lowly plant life swarm on the earth in this earliest known era, but that the rays of the sun also reached the surface. There was at that time no impenetrable cloud mantle darkening a primordial atmosphere.

It has long been held, but on insufficient grounds, that the mere presence of limestone and iron-ore constitutes also indirect evidence of life. This, however, is a conclusion not soundly based. The precipitation of limestone would go on in shallow, wave-agitated waters even without the presence of life, provided that an atmosphere containing carbon dioxide reacted through the agency of rain upon a land of igneous rocks. It seems entirely probable that denitrifying bacteria lived then as now and took advantage of the presence of the calcareous salts, but it is seen that this must be proved by detailed studies of the limestones and cannot be assumed as a cause of their existence. As to the mode of formation of the pre-Cambrian iron-ores, Van Hise and Leith have definitely expressed the reasons for believing them chemical precipitates due to ferrous salts in ocean waters reacting with solutions of alkaline silicates (Monograph 52, U. S. Geol. Survey, Chapter XVII, 1911). The subsequent partial oxidation of these ores to the ferric form, however, implies the presence of free oxygen, and this is an indirect suggestion of the existence of plant life, though not so strong as the existence of graphite in sediments. The mere presence of limestone and iron-ore cannot, therefore, be used as evidence of life in the Archeozoic. (Barrell.)

Conclusions Regarding the Archeozoic

Absence of Oldest Archeozoic Rocks. — Geologists have as yet no evidence as to what took place in earliest Archeozoic time,

nor have they seen the original foundation upon which the Coutchiching, Keewatin, and Grenville series rest. The evidence, therefore, is positive that the former foundation of the Canadian Shield, that is, the rocks older than those now resting upon the Laurentian granites, has been displaced or re-fused by the great upwellings of these, the most ancient of known igneous rocks. With Coleman we therefore agree that if the earth ever passed through a period of great heat, it was at a time too remote in the past to leave a geological record. Or, in the language of Adams and Barlow, " the probability of finding at any accessible portion of the earth's surface the original basement on which sedimentation was inaugurated is somewhat remote."

Known Archeozoic Rocks. — From Labrador to Lake Superior, through a distance of more than 1400 miles, there extends along the southern side of the Canadian Shield the great Laurentian geosyncline, apparently deeper in the northeast than in the southwest. Along the southern side of this trough east of Lake Huron occurs the very thick Grenville series of limestones, which becomes more and more metamorphosed, folded, crumpled, and elevated to the north. Through this trough at the north has broken a long northeasterly-southwesterly trending mass of granite, having the general direction of the present north shore of the St. Lawrence River, and followed on the north, not by limestones, but by sandstones and conglomerates (Adams). In the Lake Huron region and west of it, volcanic activity was very pronounced and lava streams, lapilli, and ashes occur on a large scale, either mixed with the water-formed sediments or making up thousands of feet of rocks in themselves. Much of the material suggests well-weathered products derived from granite and gneiss; but the arkoses, which are wide-spread and thick, probably imply a cool and moist land surface. All varieties of geological work seem to have been under way in Archeozoic time as they have been ever since; and there is no evidence of special primeval conditions different from those known to later geology (Coleman).

The most striking features of the Archeozoic formations are, then, that they are more largely igneous, and more profoundly and universally deformed and metamorphosed than those of subsequent eras (see Figs. 256 and 259).

Length of the Archeozoic. — That Archeozoic time was exceedingly long is evident from the thickness of the Grenville series alone, 94,000 feet, of which between 50,000 and 60,000 feet is marble.

Absence of All Fossils. — Of fossils there is no undoubted evidence, but that life, both of plants and animals, in at least the unicellular stage of evolution, was present seems to be attested, as previously discussed (page 546).

Mountain Building and Erosion Records

Laurentian Revolution. — After an exceedingly long era of tranquil events and the accumulation of vast depths of marine and some continental deposits, Archeozoic time passed into the closing stages, which were likewise of long continuance. The event of first importance was the Laurentian Revolution, marked by crustal unrest and disruption, not only throughout the Canadian Shield and North America, but possibly the world over. It is now known that almost everywhere over the shield the Archeozoic rocks were invaded by two series of Laurentian bathyliths of pinkish granites. These are seen almost everywhere at the surface of the shield. The first of these invasions was of closing Archeozoic time, but the second one is now considered to have been of early Proterozoic time. To keep these two important periods of intrusion distinctly apart, it is proposed to follow Van Hise and Leith, and Lawson, in retaining Logan's term Laurentian for the first granitic invasion and Algomian for the second (see Fig. 352).

"The first of the granites," says Barrell, "Lawson continues to call the Laurentian, the second great invasion he has named the Algomian, and he places it after the Huronian. Other writers, however, place the second before the Huronian; Coleman, moreover, considers it probable that the Laurentian of Logan's original area belongs to the later invasion, not the earlier, and the name refers more properly therefore to the later of the two. Such a conclusion leaves the earlier granite and gneiss nameless. In order to avoid confusion until more definite knowledge is attained, the writer proposes to call the older the *Paleolaurentian*, the later the *Neolaurentian*. Probably much of the fundamental granite gneiss for a long time, if ever, cannot be classified positively into either the one or the other division. For such areas the general name of *Laurentian* will continue to apply, and may include rocks of two widely different ages."

Laurentian Mountains. — The hot molten magmas welled from the depths of the earth and rose into the sedimentaries and volcanics of older date, re-melting and assimilating them in part, and raising them everywhere into the "domed mountains" or "bathylithic mountains" of Coleman. As geographic names are applied to mountains, these may be called the *Laurentian mountains*. These bathyliths, Coleman says, varied in length up to 60 miles, and were somewhat elongate from west to east or from southwest to northeast. This general east-northeast trend of the basement

structures doubtless reveals the axial relations of the Archeozoic mountain ranges. He thinks they probably were not continuous chains, but consisted rather of groups of domes of various sizes and heights. The thrusting came from the southeast, and it may be that because of this we can also see in these movements compensating ones leading to the origin of the Atlantic, or at least indicating the first known deepening of this ocean and the origin of the Interior epeiric basin.

With the rising of the Laurentian mountains went the arching, folding, crumpling, and metamorphosing of the Archeozoic formations. The Keewatin schists are now seen wrapped around the bathyliths, with dips in places of from 60° to 90°, but it should be remembered that what we now see are the combined results of three revolutions and a number of disturbances to be described in later pages. All of these movements were of pre-Cambrian time.

Ep-Archeozoic Interval. — While the Laurentian mountains were building and afterwards, erosion was at work degrading them, and on the basis of the marked unconformity existing between the Archeozoic and Proterozoic formations, it is clear not only that the interval was long but that the amount of erosion was great. How long this interval lasted and the amount of record removed is not known, but that the length of time was very great is evidenced by the fact that all geologists who have worked with the formations of the Canadian Shield are agreed that the greatest break in the pre-Cambrian formations occurs between the Archeozoic and Proterozoic systems of rocks. Van Hise and Leith say that in the Lake Superior area the Archeozoic was nearly base-leveled before the deposition of the Proterozoic. The contrast of the systems in vulcanism, in metamorphism, and in relative amounts of sediments is striking. Any one who has seen the evenly bedded Proterozoic sediments resting upon the erosion edges of the gnarled and contorted complex of Archean schists, gneisses, and other rocks would not question the conclusion that this unconformity is a great one and required for its development erosion throughout an eon of time.

CHAPTER XXVIII

THE EARLY PROTEROZOIC SUB-ERA

Extent and Thickness of the Proterozoic. — The Proterozoic era, or the time of first known life, represents a vast lapse of time, for in Ontario and the Lake Superior country it includes, as now defined, the making of a mountain system and its complete removal through erosion, with a maximum accumulation of about 74,000 feet of sediments and 22,000 feet of volcanics. Of these formations 20,000 feet of coarse detritus (coarse sandstones, conglomerates, and arkoses) were developed in the earliest part of the era, 25,200 feet of various kinds of sediments in the quiet middle time of main sea invasion, and 28,670 feet of coarse continental sediments, along with 22,700 feet of volcanics, in the troublous closing period. On the other hand, in the Rocky Mountains area, upward of 37,000 feet of sediments are still present, consisting mainly of sandstones and shales along with more than 7000 feet of limestones. For the distribution of the Proterozoic formations see maps, Figs. 348 and 356.

These events are grouped as follows, the oldest at the bottom:

Table of Proterozoic Events

Epi-Proterozoic interval of erosion.
Late Proterozoic sub-era, or Algonkian time.
  Late Algonkian time.
    Keweenawan series of continental formations.
      Break in record.
  Middle Proterozoic or early Algonkian time.
    Animikian marine series, with great iron formations.
    Epi-Huronian interval.
    Huronian series of glacial, continental and marine formations.
Early Proterozoic sub-era.
  Ep-Algomian interval, and formation of Laurentian peneplain.
  Algomian Revolution, mountain building, and second intrusion of Laurentian granites.
  Sudburian series of delta deposits.

Early Proterozoic Time

Huronian of Logan. — The original "Huronian system" of Logan has undergone much investigation since he studied it in the

eighteen-sixties and seventies, due to the great mining industries recently developed in Canada. It is highly to the credit of the later Canadian geologists that they have shown how vastly much more time is embraced in the Huronian system of Logan than was originally thought possible. In the past few years it has been learned that this time produced two distinct series of formations, separated from each other and from those below by periods of mountain building and of profound erosion. For this reason the Proterozoic is here divided into two sub-eras, though it is probable that future work will prove, as seems already indicated, that both are of era rank, and that the term Early Proterozoic will have to be given up for another in harmony with Archeozoic and Proterozoic. In this event the pre-Cambrian or "Archean" of older geologists will consist of three eras and not of two as presented in this book.

Fig. 350. — Vertical strata of Sudburian quartzite, near Whitefish, Ontario. Photograph by A. P. Coleman. From Yale University Press.

Sudburian Series. — This series of formations, apparently wholly of delta origin, attains to an estimated thickness of 20,000 feet and consists chiefly of white quartzites, which are well exposed from Lake Huron north to Sudbury, and beyond for 100 miles in Ontario (Fig. 350). These regularly bedded sands, mainly of vein quartz or the quartz of granites, about 15,000 feet thick, are cross-bedded throughout, with thin zones of interbedded slate, which represent from 2 to 13 per cent of the total thickness of the deposits. Carbonaceous material, however, is completely absent in the Sud-

burian, which is a cleanly washed sand of fairly equal grain, coming apparently from the north and transported by long rivers to a wide delta built into the epeiric sea that then lay over the United States.

The lower part of the Sudburian of Coleman, of variable thickness up to 5000 feet, is heterogeneous in composition. In places there are arkoses, the broken-up material of granite, as much as 1000 feet thick, and in others, regularly and cross-bedded thin alternations of grits and muds with angular quartz grains. The arkoses and graywackes full of feldspars are found in close association with areas of granite, and are therefore the disintegrated material of this old floor. As a rule, however, in most places the Sudburian has a basal conglomerate, which at Sudbury has a thickness ranging in places up to 5000 feet. The basal deposits include scales of

Fig. 351. — Sudburian quartzite, crumpled by granitic intrusions, near Cutler, Ontario. Photograph by A. P. Coleman. From Yale University Press.

chlorite or sericite in abundance, well-rounded pebbles and small boulders of several kinds of granites, vein quartz, quartzite, greenstone (metamorphosed volcanics), and banded jasper. These materials are from the older Laurentian granites and the Keewatin volcanics and iron deposits. The coarse basal fragmental material, in which the feldspars are undecomposed, is thought to indicate a cool and moist climate, though later Sudburian time may have been less severe.

At the top of the Sudburian occur very basic lavas with fine pillow structures. The dikes related to these flows cut all the

older rocks. These effusives, however, indicate a series of small volcanoes of no great geographic extent.

In places where the Sudburian is not intruded by the later eruptives, it is but little altered, so that the original bedding, cross-bedding, and even the ripple-marks may still be seen on weathered outcrops. Where intruded by the granites, however, the Sudburian is much metamorphosed. All of the Sudburian is deformed, tilted or sharply bent, with an average dip of 45°, the strata rising toward the granite bathyliths of later intrusion. For this reason, the Sudburian series is sharply marked off from the higher Huronian, which usually lies nearly flat or is but gently folded.

Similarity of Sudburian Formations to those of Later Eras. — As the Sudburian deposits are so very ancient geologically, it is consequently desirable to point out the physical conditions under which they must have formed. This has been done for us by Coleman, who states that except for the absence of fossils and the fact that in places they have been much metamorphosed, the rocks of Sudburian time resemble in every way the later sediments. Every type of rock has its counterpart in subsequent ages; and where the later rocks have undergone deforming stresses or have been penetrated by large masses of eruptives, as in various mountain regions, even the metamorphic characters of the Sudburian are found repeated in them, as in the Paleozoic schists. The apparently modern nature of the Sudburian is the most surprising impression made on the observer while in the field. From this we conclude that the atmosphere in character and composition must have resembled that of later times; water did its work then as now, the extremes of heat and cold seem to have been normal, and there is little doubt that plants and animals existed; in a word, the world was then organized along the lines which have been predominant ever since. There is no suggestion of the existence of primitive physical conditions radically unlike those which were to prevail in later times, and there is no evidence that the earth's internal heat was greater then than it is now.

Algomian Revolution. — After the close of Sudburian time came the second marked upwelling of granite bathyliths and the making of the Algomian mountains, so called by Lawson in 1913 from a locality in western Ontario. It seems that this second rising of granite from unknown depths was even more profound than the earlier one, the Laurentian, which gave rise to the Laurentian mountains at the close of the Archeozoic, as mentioned in the previous chapter. (See also Fig. 352.) How much of the Sud-

burian deposits was remelted and assimilated by the rising granites no one knows. The most recent writer on these formations and events, Coleman, concludes as follows:

" The sediments of the Sudbury, Temiscaming, Doré, and Seine series [which together make up the Sudburian] were upheaved, tilted, and thrown into folds along with the older groups of rock by the floods of granitic magma making up the Laurentian [of Logan]. From the attitude of their present remnants it is evident that great ranges of mountains with a trend of about N. 70° E. resulted from this enormous welling up of molten or plastic material. From the coarseness of the grain of the granites and gneisses enclosing or adjoining the sediments, it is evident that they cooled at great depths and slowly."

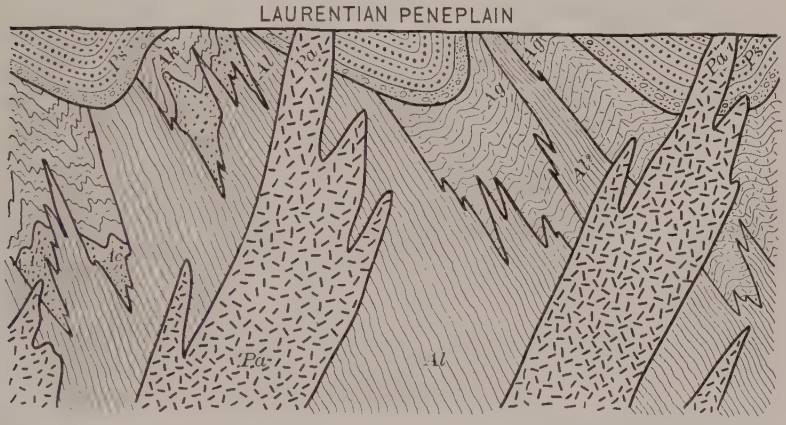


Fig. 352. — Diagram to show present relation of two series of granitic intrusions to older strata of Archeozoic and Early Proterozoic time. Drawn by Barrell. The order of events shown on the drawing is as follows, beginning with the youngest at the top: (7) Ep-Algomian interval and peneplanation; (6) Algomian Revolution, granitic intrusions (*Pa*), and folding of Sudburian (*Ps*); (5) Sudburian sedimentation (*Ps*); (4) Ep-Archeozoic interval and peneplanation (heavy line at base of *Ps*); (3) Laurentian Revolution, granitic intrusions (*Al*), and folding of Archeozoic formations; (2) Keewatin lava outflows (*Ak*), and Grenville sedimentation (*Ag*); and (1) Coutchiching sedimentation (*Ac*).

Granite Injections. — Though granites dominate the rocks of the Archeozoic and Early Proterozoic formations the student must not conclude that they are restricted to these times. Granites are known in the hearts of the mountains of almost any date (see page 364), though they are exposed less in those of Cenozoic time than in those of older age, partly because of the shorter time the Tertiary rocks have been subjected to profound erosion.

Ep-Algomian Interval. — After the Algomian mountains had been built, their destruction followed, and their removal by erosion must have been an extremely slow process. Coleman states that thousands of feet of granite, gneiss, greenstone (metamorphosed basalt), quartzite, and schist conglomerate must have been consumed by the weathering processes. The Algomian mountains, occupying most of the Canadian Shield, were during this interval carved down to a peneplain, laying bare the roots of the mountains; this is the most tremendous and wide-spread example of base-leveling known in the history of the world. The erosion which has since taken place over the Canadian Shield is insignificant in comparison, so that the present peneplain is in part a close approximation to this ancient land surface. How vast a time was required for the removal of millions of cubic miles of hard rock from this great area (the shield has an area of 2,000,000 square miles, see Fig. 365), and whither the material has been transported, one can scarcely guess, though it seems probable that it lies deeply buried in the oceanic basins.

Laurentian Peneplain

Original Character of the Peneplain. — The present surface, Coleman says, "is a close counterpart of that on which the Huronian was deposited and from which in places its basal conglomerate is now being stripped. In fact, it almost appears as if the present uneven plain of comparatively low relief, formed everywhere of mounds or ridges and depressions, is part of the little changed pre-Huronian continent. . . . It looks as though far the greater part of the peneplanation was already complete in Huronian times." It should be added, however, that much of the surface had been repeatedly covered by the sea, even as late as Devonian time, and that the last of this covering has been removed only comparatively recently. Other parts not so protected by later Proterozoic or Paleozoic sediments must have had the pre-Huronian surface destroyed during those ages. Since no pronounced warping or folding has since taken place, however, these various facets of erosion of the present surface developed in various periods must shade into each other. The recently exposed pre-Huronian peneplain occupying wide areas around the basal Huronian might properly be called the Ep-Algomian facet of the Laurentian peneplain. Coleman continues, "The basal Huronian conglomerate has perfectly sealed up and preserved for us parts of the ancient surface. At some points the rock beneath had been weathered in

place, and one can observe the fresh, unbroken material growing fissured in the upper parts and passing into a breccia of fragments and finally into coarse sand, all now firmly cemented into rock."

"The surface beneath the Huronian represents therefore a mountain region degraded by subaërial forces to a peneplain, somewhat hummocky and irregular, but in the main of low relief [see Fig. 353]. In many, if not in all places, its surface was deeply mantled with the disintegration products due to this secular decay, but before the deposition of the Lower Huronian some parts had not only been swept bare of débris but had been scoured and smoothed to the solid rock."

Fig. 353. — Laurentian peneplain as seen from Lake Michikamau, Labrador. Photograph by A. P. Low. From Yale University Press.

Present Character of the Canadian Shield. — The greater part of the present surface of the Canadian Shield (see map, Fig. 365) is an undulating plain replete with an intricate series of connected lakes and rivers (Fig. 353); near the center of it lies a depressed area containing Hudson Bay, a body of marine water with an average depth of 420 feet. From this central basin there is an upward slope in all directions toward the Height of Land. The general level of the plain above the sea is about 1500 feet, and the local differences of level are usually under 150 feet, though rarely they may be as much as 500 feet above the general plain.

The shield as a whole rises slowly to the east, and in central Ungava is about 2400 feet above the sea. Along the eastern margin of Labrador are rugged mountains that in the north attain to 6000 feet, and certain peaks even reach 7500 feet. In fact, it may

be said that a mountainous tract extends for 2000 miles from Belle Isle north to Cape Sabine in Smith Land. This rough topography, and also that along the southern margin east of the city of Quebec, is youthful in form, and the deformation of the shield here is thought to have arisen in late Tertiary or early Pleistocene time, the movements continuing to recent times.

Suess would limit the shield to Canada, as above defined, but Adams and other geologists include in it Greenland and the Adirondacks of New York. The latter region now reaches a height on a few mountain peaks of about 5000 feet above the sea, the average elevation being about 2000 feet, an altitude which is also the result of Cenozoic upheaval of a regional character.

Geologic Structure of the Canadian Shield. — Most of the shield, in fact it is said four fifths of it, is composed of gneisses and gneissic granite, the rocks of Logan's Laurentian system. There are, however, according to Adams, " distributed over the surface of the shield, chiefly in the form of long and relatively narrow belts, certain very ancient sediments, pre-Cambrian in age. These belts occupy the position of synclinal folds which have sagged down or have been forced down into the igneous rocks of the Laurentian which surround and underlie them. These belts in the southern half of the shield have a prevailing northeast and southwest strike, indicating the trend of ancient folds, which probably developed as mountain ranges in pre-Cambrian times, having a general direction parallel to the present course of the river and gulf of St. Lawrence. One of the longest, best defined, and most striking of these folds is the geosyncline, which, starting from the north shore of Lake Huron, extends past Lake Temiscaming, Lake Abitibi, to Lake Mistassini, and thence on in a northeasterly direction till it is lost in the unexplored portion of Labrador peninsula. The original Huronian area of Logan lies in this belt."

Origin of the Central Interior Basin

We have seen that at various times during the pre-Cambrian the Canadian Shield was extensively deformed and broadly though slightly elevated. The same is true for the eastern and western border lands, Appalachia and Cascadia, but the great medial southern part of the continent seems not to have been so affected. It continued a low-lying area, a continental basin that stood but little above the average sea-level (see Fig. 365). Wherever this basin has subsequently been upwarped and the Paleozoic forma-

tions removed through erosion, there are revealed the same kinds of rocks as those of the shield. From this it appears that the Canadian Shield, Appalachia, Cascadia, and Columbia have been as a rule positive in their movements (see page 228 and Fig. 185), while the continental basin has only been subpositive or stationary. With the introduction of Paleozoic time the continental basin appears to have been more negative, for we shall see it repeatedly covered by the shallow Central Interior sea, but the average depression for all of Paleozoic time did not exceed 2000 feet. This is more especially true of the region west of a line extending from Sandusky to Cincinnati, Ohio, and thence to Nashville, Tennessee.

CHAPTER XXIX

THE LATE PROTEROZOIC SUB-ERA

Early Algonkian Time

Late Proterozoic time is replete with interest because at the very beginning of this sub-era we have not only unmistakable evidence of a glacial climate, but also the first positive evidence of plant life in the form of calcareous algal secretions. The divisions of Late Proterozoic time are shown on pages 444 and 551.

Definition of Algonkian. — Late Proterozoic time may also be known as *Algonkian*, a term used in a wider sense by the United States Geological Survey for the "sedimentary formations and their metamorphosed equivalents with associated igneous rocks beneath the Cambrian and resting upon the Archean complex" (Van Hise and Leith). At the time the name was proposed, there was thought to be a sharp distinction between the earlier era, the Archean, characterized by dominance of igneous rocks, and a later one, having in the main sedimentary deposits. The recognition, however, of a second great granitic invasion, and the further fact that igneous rocks alternate with periods of sedimentation as far back as geologic history is known, largely destroy the value of the divisions Archean and Algonkian. The latter name has reference to the land of the Algonkian Indians — the Lake Superior-Ontario-Hudson Bay country — where these rocks have long been studied.

Basal Tillites of the Huronian. — One of the most surprising of recent discoveries in Geology was the finding by Coleman of tillites (morainal deposits of glacial till or bowlder clay, hardened into stone, see page 134 and Fig. 354) in the Huronian formations of Canada, and the consequent establishing of the occurrence of a *glacial climate* thus early in the history of the earth. Over the wide Laurentian peneplain just described, there is found in the country to the north of Lake Huron a basal conglomerate that often includes facetted and striated bowlders of various kinds of rocks (Fig. 355). In the tillites occur, locally, thick zones of slate and water-formed conglomerates and quartzites that indicate interglacial warmer climates.

Fig. 354. — Eroded exposure of the Lower Huronian tillite, near Cobalt, Ontario. Photograph by A. P. Coleman. Yale University Press.

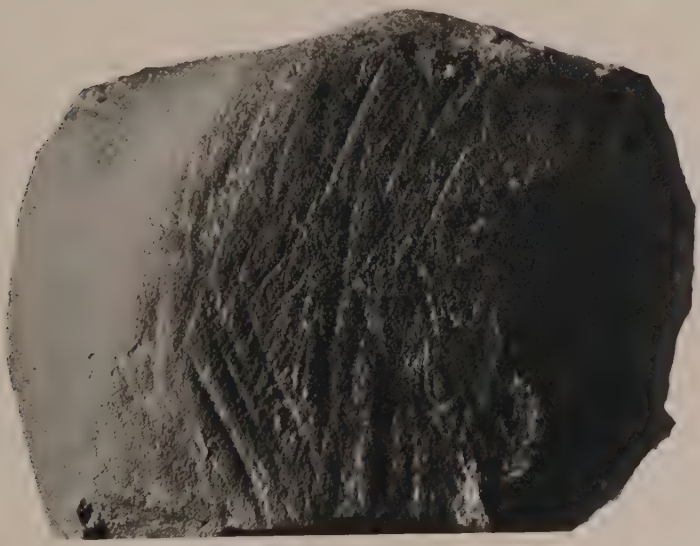


Fig. 355. — Striated bowlder of the Lower Huronian tillite, Cobalt, Ontario. Photograph by A. P. Coleman. Yale University Press.

The whole thickness of glacial beds is usually not more than 500 or 600 feet, somewhat in excess of the thickness of the recent Pleistocene glacial and interglacial beds at Toronto. This Huronian tillite is known to cover an area of 1000 miles from west to east and 200 miles north and south, down to 42° north latitude, and rests upon a nearly plane surface that still lies not far above sea-level. It is the material of a continental ice sheet which deposited its content of rocks and earth upon the land.

"Bowlders of granite and greenstone with diameters up to 2 or 3 feet are common and larger ones measuring 5 feet through are occasionally met. . . . These bowlders may be well rounded, subangular, or angular. They may be crowded into a mass of large and small stones cemented together, or they may lie sparsely scattered in a fine-grained matrix, the red granites showing up sharply from square yards of dull greenish gray ground mass. Generally no marked stratification can be seen in the coarser conglomerates, though associated pebble conglomerates and slates may be well stratified. . . . The matrix and the bowlders enclosed vary greatly from point to point, roughly corresponding to the character of the rocks beneath, and the rock strongly suggests a glacial moraine in some cases and bowlder clay in others." (Coleman.)

Huronian Sedimentaries. — Above the basal tillites occur gray quartzites that rarely are conglomeratic and attain to 1000 feet in thickness. Then follows a marine limestone about 300 feet thick, and this limestone in the Lake Huron region is thought to be of the same age as another limestone, blue and gray in color and up to 500 feet thick, situated at the base of the Huronian series in the Rainy Lake area north of Minnesota. The latter limestone bears the oldest undoubted fossils known, certain forms of calcareous algal secretions, of which more will be said later.

Over the limestone of Lake Huron appear arkoses reaching 2300 feet in thickness, followed by 2150 feet of red jasper conglomerates, 2970 feet of white quartzite, 400 feet of chert with limestone and slate, and 1500 feet of white quartzite. These deposits are thought to be those of a delta, and the arkoses and green quartzites suggest a cool and moist climate following the Huronian ice age.

There appears to have been no volcanic eruption in Huronian time.

Epi-Huronian Interval. — The Huronian was not followed by a time of mountain building, but by slight bodily elevation or warping. The land condition of the shield thus brought about is thought to have been of long duration, and Lawson believes it of great enough importance to be called the *Ep-Archean interval.* In point of fact, however, it may be said that, although the Canadian Shield has undergone many movements, none of them after the Algomian Revolution was of a marked character until that of

the recent Pleistocene time, when the eastern and southwestern borders underwent elevation, as is now to be seen in the young topography of the areas mentioned.

Animikian or Iron Series. — The formations of Animikian time have a wide though scattering distribution over the Canadian Shield, the sea, it is thought, having transgressed far and wide over the older rocks. Most of the deposits are of marine origin, though some appear to be of a continental character. However, the Animikian formations are not now of universal distribution over the shield. On the contrary, the areas are widely isolated

Fig. 356. — Surface distribution of the known Animikian and Keweenawan formations. After Coleman. Yale University Press.

and appear in the main to be remnants preserved from erosion in the down-folded or gently down-warped basins in the older rocks (Fig. 356). The bounding lands of these seas are as yet unknown.

Everywhere the Animikian strata lie nearly horizontal and are very little metamorphosed. In the Penokee area of Michigan the formations that remain after their long exposure to the erosive forces are still 14,000 feet thick, but elsewhere they are usually reduced to a maximum of about 6000 feet.

The deposits of the Animikian may begin with a basal conglomerate of pebbles of the Keewatin schist and Laurentian gneiss. This passes into chert or jasper that may be banded or oölitic, or into beds of impure limestone or dolomite with chert. Higher in the series there are great thicknesses of thinly laminated carbonaceous slate with large concretions of marcasite, and it has been calculated that if all of the carbon in these argillites (6 to 10 per cent) were concentrated, it would make a bed of anthracite 200 feet thick. There is also much sandstone. Near Port Arthur the Animikian is interbedded with sills and dikes of diabase or trap of Keweenawan age, the sills varying from an inch up to 200 feet or more in thickness, and near Sudbury there are interbedded tuffs with a depth of 3800 feet.

"The wide-spread shallow seas of the Animikie," says Coleman, "had one feature scarcely repeated on the same scale in later times, the deposition of iron compounds with associated silica. In nearly all of the Animikie areas there is an 'iron formation' [in places as much as 1000 feet thick], with cherty ferruginous carbonate or oölitic greenalite or jasper . . . as the initial stage, from which are formed by secondary causes small or large bodies of ore, culminating in the immense and rich deposits of the Mesabi to the southwest of the shield in Minnesota." Other great fields occur in the Penokee-Gogebic region of Wisconsin and Michigan, and in the Menominee area, which lies chiefly in the latter state.

Lake Superior Iron Mines. — The hematite ores found along the south and west sides of Lake Superior in the Archeozoic and Proterozoic formations are in the main (70 per cent) from the Animikian series. Most of the richest ores occur near the surface and for 1000 feet downward. Originally the iron formation had a content of about 25 per cent of metallic iron, but in places it has been concentrated and in these, which form the mining areas, the amount in the ores now mined is about 59 per cent. The Marquette, Michigan, field was opened in 1849, and that of the Mesabi in 1892. In 1912 Minnesota produced more than 34,000,000 long tons and Michigan about 11,000,000, making up about 82 per cent of all the iron-ores mined in that year in the United States. On account of the enormous scale upon which these rich mines are now worked they will become exhausted during the present generation. Vast bodies of lower grade ores remain, however, which will gradually come into economic use, but their lower content of metal will mean, in so far as that factor is concerned, a higher price of iron. The rich ores utilized in the present generation have been no small factor in the present great industrial expansion of the United States and Canada.

Late Algonkian Time

Lower Keweenawan Sediments. — Geologists are agreed that there is a distinct break in the record between the Animikian and the Keweenawan series of formations. Moreover, the sediments of the former are of marine origin, while those of the latter are held to be of continental deposition. Some geologists hold that the

Keweenawan should be referred to the Paleozoic, but the trend of opinion is that it should be regarded as the closing period of the Proterozoic era, a belief that is followed in this book. The Keweenawan is characterized by enormously thick deposits, both of sediments and lavas, in geosynclines, and also rather widely over vast areas. The igneous activity became greater in its middle and upper portions.

At the base, from Wisconsin eastward, there are conglomerates, well stratified, coarse, red and white sandstones interbedded with conglomerates, thin impure limestones of various colors, and shaly rocks, the whole having a thickness of from 300 to 1400 feet. These are also penetrated by dikes and sills of diabase or trap of Upper Keweenawan time. The sediments are largely derived from the Laurentian granites, but red jasper pebbles of the iron formations also occur. Ripple-marks are common, the sandstones are often feldspathic and might be called arkose, and the shales have mud-cracks, all of which are indicative of continental origin. Further, the prevailing color is red, like the Triassic of the Connecticut valley, suggesting semiarid conditions and complete oxidation, and in this, according to Van Hise and Leith, the Keweenawan sediments differ greatly from the earlier series; the absence of carbonaceous beds is also strikingly different from the conditions found in the Animikie sediments.

Upper Keweenawan Volcanics. — The closing period of the Proterozoic record is marked in the region of Lake Superior and elsewhere by a tremendous outpouring of volcanic materials upon the dry land, probably not by volcanoes but rather through fissures. Most of the formation, according to Coleman, " consists of basic lava flows, variously called trap or diabase or melaphyre, some being really basalts, but there are also more acid [feldspathic] flows, referred to as porphyries and felsites, really rhyolites. In subordinate amounts ash rocks and lapilli are found between the lava sheets, and the [interbedded] conglomerates and sandstones [and shales of small amounts] are made of almost contemporary material, especially of fragments of the rhyolites and porphyries." It is very difficult to decide whether the eruptions of Keweenawan time were greater than those of Keewatin.

One of the thickest series of lavas known on the Canadian side of Lake Superior occurs on Michipicoten Island where a section was measured with a thickness of 11,230 feet, only a small part of which consists of sediments. In northern Wisconsin and Michigan, Van Hise and Leith give the maximum thickness of their

Middle Keweenawan (after allowing for initial dip during accumulation) as upward of 30,000 feet. Of this, from five eighths to eight ninths is igneous material, the rest being red conglomerates and red sandstones derived from the volcanics.

Over the "Middle Keweenawan" of Wisconsin and Michigan lies the local "Upper Keweenawan," made up of conglomerates (800 to 4000 feet), sandstones (15,000 feet), and shales (100 to 400 feet) attaining a total thickness of about 20,000 feet. All of this material is, however, detritus from the igneous Keweenawan, and does not signify a long interval of erosion, because of the soft nature of the volcanics and the high and rough topography of the lava field. However, Van Hise and Leith say that Keweenawan time may have been as long as the Silurian, Devonian, or even the Cambrian.

The volume of known igneous material extruded (estimated as 24,000 cubic miles) was accumulated in a sinking field, and in this way arose the Lake Superior geosynclinal basin, which is almost devoid of subordinate folds. In other words, the molten material as it rose to the surface permitted the upper formation to sink in. In other areas, however, the Keweenawan rocks still lie almost horizontal, and in general their appearance is not unlike similar Paleozoic formations, though block faulting is common.

Upper Keweenawan Metals. — From the human and economic point of view, the advent of the Keweenawan lavas was one of the most important events in the pre-Cambrian history of the Canadian Shield, since most of the valuable ore deposits of the region, so far as known, are connected with eruptions of this age. At Thunder Bay the *silver ores* of Silver Islet and other mines were supplied by the Keweenawan diabase dikes and sills. The unrivalled mines of *native copper* in Michigan belong to the amygdaloids and conglomerates of Keweenaw Point, and similar ores of native copper, perhaps on a larger scale, exist in the extensive area of amygdaloids east of Great Bear Lake and near Coppermine River in the extreme north of the shield. (Coleman.)

The native "low grade" copper ore of Michigan was discovered by Douglas Houghton in 1830, though worked long before by the Indians. The area in which it occurs is 70 miles long by 3 to 6 miles wide. The famous Calumet and Hecla mines were opened in 1846, and in the following year Michigan produced 213 long tons of copper. In 1911, the yield was 110,000 tons, valued at $27,480,000.

"The Sudbury [Ontario] deposits of *nickel and copper*, including much the largest mines of nickel in the world, are connected with a sheet of norite-micropegmatite probably of Keweenawan age; and Miller has concluded that the singularly rich silver veins of

Cobalt have derived their ore from a great diabase sill which ascended into the Cobalt conglomerate at this time.

"The Keweenawan eruptives seem to have brought with them copper, nickel, and silver in large amounts, cobalt, gold, platinum, and palladium in much smaller amounts; and if the iron mines are left out of account, almost all the metalliferous deposits of the southern margin of the Canadian Shield have resulted from the coming of its dikes or sheets or lava streams." (Coleman.)

Fig. 357. — Limestones and cherts of the Proterozoic (Castle Mt. group), Flathead County, Montana. Photograph by Walcott, U. S. Geol. Surv.

Proterozoic of the Cordilleras

The best known and thickest sections of Proterozoic formations in western North America occur in western Montana, eastern Idaho, and British Columbia, north to at least 54° north latitude (see Fig. 357). Upward of 37,000 feet of sediments, mainly sandstones and shales, are exposed in the combined sections. In the Cabinet Range, Montana, the thickness is about 35,000 feet (Calkins). A striking feature of the Proterozoic formations of the Cordilleras, Lindgren states, is the small amount of igneous materials. Diabase intrusions of small areal extent are known, and it is probable that there are also some basalt flows. North of the Inter-

national Boundary, however, extensive intruded sheets are referred to this period.

The Cambrian overlies the Proterozoic strata in Montana and British Columbia with apparent conformity, and yet there may have been as much as 16,000 feet locally removed through erosion preceding the overlap mentioned. In the lower part of these sections occur three great limestones, pure and impure, that have thicknesses ranging between 2000 and 4800 feet. It is in these calcareous zones that lime-secreting algæ abound. The bulk of the sediment, however, is sandstone, and it is significant that above the basal portion much of it is red in color, ripple-marked, and sun-cracked. As the clastic portion thickens to the west at the expense of the limestone, we see that it is from this direction that the sediment was mostly derived. The inference seems to be that the earlier sediments are of marine origin, while the later formations are either delta deposits or are continental and of a semiarid climate. From this it appears that the succession harmonizes well with that of the Middle and later Proterozoic of the Canadian Shield. All of these vast piles of rock came from a land which then included California and the region north into western British Columbia.

Fig. 358. — View east up Colorado River, near mouth of Bass Canyon, Arizona. The print is the reverse of the view in nature. On the left and above are horizontal Paleozoic strata resting on peneplained monoclinal beds of the Proterozoic (Unkar). The latter lie upon the tilted and peneplained Archeozoic (out of view) in the Granite Gorge of the river. Photograph by L. F. Noble.

In the *Grand Canyon*, Arizona, occur the Chuar and Unkar formations with a thickness, remaining after an unknown amount of erosion, of nearly 12,000 feet, most of which is sandstone, while of limestone there is only 435 feet, and that near the base. The sediments are at first of marine origin, but quickly pass upward

into continental deposits (Fig. 358). These formations rest on the peneplained surface of the highly deformed Archeozoic strata, and both were again elevated into mountains and eroded to sea-level before the Paleozoic era began, for the horizontal Cambrian strata rest upon the peneplained older formations. In other words, after the deposition of these deposits of Proterozoic time, the rocks of the Colorado plateau were profoundly folded and elevated into a monoclinal attitude, and the resulting mountains were presumably as high as the present Alps. How long it will take to reduce the Alps, with the Matterhorn standing at 14,780 feet above the sea, no one knows, and yet it probably took as long, late in Proterozoic time, to remove the monoclinal mountains of western Arizona. The length of this time is now indicated by a marked unconformity, and as the movement falls in a time of world-wide deformation, it may be known as the *Grand Canyon Revolution* (see Figs. 34, 35, 349 and 358).

Close of the Proterozoic

Epi-Proterozoic Interval. — Erosion intervals and unconformities are of very variable duration in the different areas of the lands. They may be so short that geologists have the greatest difficulties in discerning the breaks, and on the other hand they may appear as if embracing nearly all of geologic time. It is of common occurrence on the Canadian Shield to find the Archeozoic formations overlain by the almost recent Pleistocene glacial deposits, and even these may be absent. It appears as if in such places no rocks had been deposited, either by the sea or by the forces of the land, since Archeozoic time, and yet geologists know that the shield has been variously covered by sheets of sediments formed at sundry times in the Proterozoic, Paleozoic, and, to a more limited extent, in the Mesozoic.

We have seen that some geologists refer the Keweenawan to the Paleozoic, but most workers hold that the formation of this series was the latest event in the Proterozoic, and that a long interval of time is unrecorded between it and the oldest deposits of the Cambrian. Further, in most places on the shield the Keweenawan was never laid down, and the Animikian and even the Huronian may have been eroded away before the seas of Cambrian time again invaded the area. Therefore, the Epi-Proterozoic interval is locally very variable in its apparent duration, but from the standpoint of the ascertained geologic record in its most complete form, it does not seem that this break can be more important

than the similar ones between the other eras. Accordingly, we may say that the interval appears to have lasted long, but as there are so few late Proterozoic fossils at hand, and therefore no record of organic evolution to guide us, the length of the interval cannot even be hinted at, as yet.

Lipalian Interval of Marine Organic Evolution. — Walcott, from his studies of pre-Cambrian formations, believes that nearly all of the Proterozoic deposits are not of marine origin, but that only at rare intervals did the oceans flow over the continents and thus bring into the seas of the lands their shallow-water life. Accordingly, he postulates the *Lipalian era* "of unknown *marine* sedimentation between the adjustment of pelagic life to littoral conditions and the appearance of the Lower Cambrian fauna. It represents the period between the formation of the Algonkian continents and the earliest encroachment of the Lower Cambrian sea."

It is hard to accept this postulate, since marine animals are known of latest Proterozoic time, and in addition these formations at many horizons have *algæ*, or seaweeds, as fossils. Since marine organisms are known and the limestones are of great thickness, there is evidence that marine waters (not necessarily as salty then as now) did for long periods of time invade North America. The Huronian seas, however, spread less widely than those of Animikian time.

Apparent Absence of Lime-secreting Animals. — The apparent absence of animals in the Proterozoic has been explained as possibly due to a lack of the proper amount of lime salts in the oceans and seas of this early era. In other words, it is held that there was no lime available for organic skeletons and hence there could be no structures that were preservable as fossils. Daly has suggested that the small amount of lime then being delivered by the rivers to the seas was quickly precipitated through the continuous decay of organisms. However, that lime salts were present in usable form for the making of organic structures is proved by the massive calcareous algæ recently discovered. That the marine waters of this ancient time may have had a different salt content, as held by Daly and Lane, and that this difference led to different physiological processes among the organisms, preventing the invertebrates from using lime in their skeletal parts, is more probably true, but that it is not the whole truth is seen in the fact that plants at least did build skeletons of carbonate of lime, while animals had chitinous coverings.

Proterozoic Climates

We learned on page 560 of the wide-spread glacial tillites in the Province of Ontario which are of the age of the earliest Huronian. This evidence, interpreted in the light of the knowledge derived from the most recent glaciation (Pleistocene), seemingly indicates a cold climate at this time for most of the world (see map for distribution, Fig. 359).

Another series of undoubted glacial tillites occurs in southern Australia and Tasmania, having a thickness of between 600 and 1500 feet. These lie just below Lower Cambrian deposits and are held to be of latest Proterozoic time. Other glacial tills, also

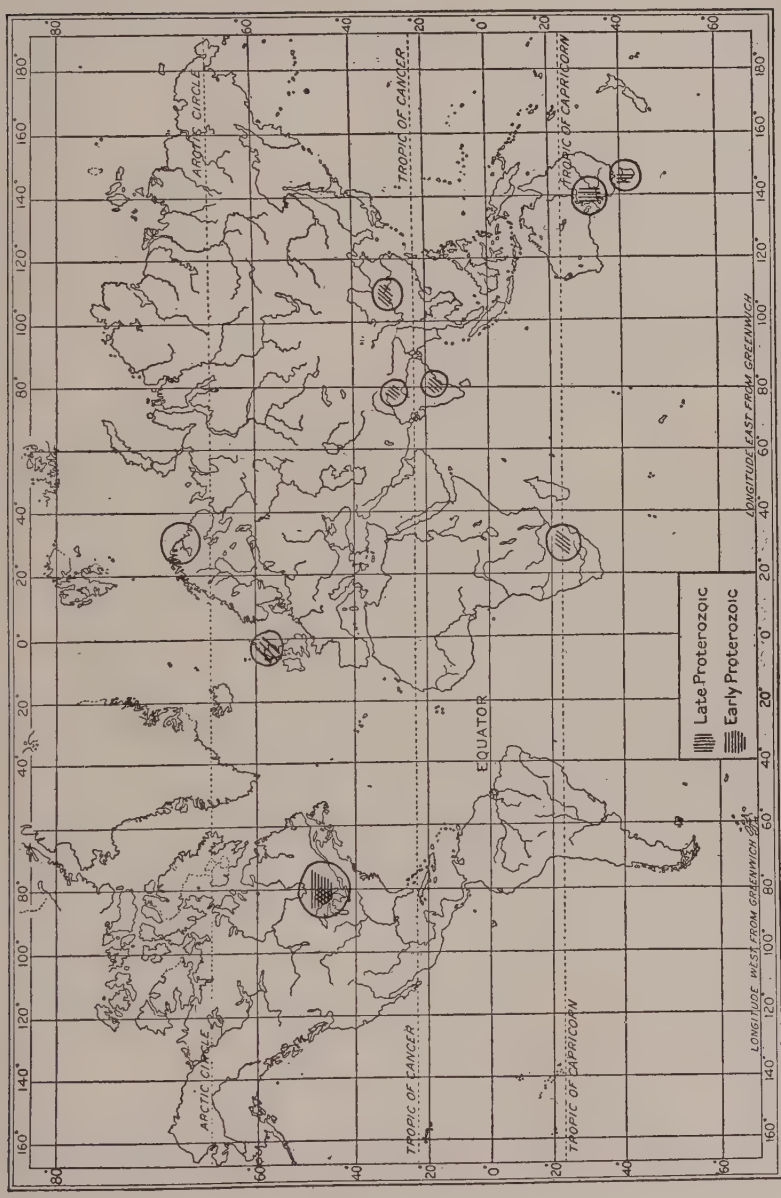


Fig. 359. — Areas of Proterozoic glaciation. Diagonal lines are areas of unknown age. The Norwegian occurrence shown by an empty circle is probably of late Proterozoic time. Carnegie Institution.

thought to be of late Protorozoic time, were made known by Reusch as long ago as in 1891, in the north of Norway, where is also preserved the scratched ground over which the ice moved. Therefore the evidence seems to indicate another cold climate for the world during the latest part of Proterozoic time.

Still other Proterozoic tillites are known in peninsular India, at Simla in northern India, and again in southeastern Africa. Finally, in China, in the provinces of the middle Yangtse River, Willis and Blackwelder have discovered unmistakable tillites. The exact age of all these occurrences is not yet established beyond the fact that they appear to be of Proterozoic time; probably some of them are of one age.

On the other hand, the very thick beds of Proterozoic limestone suggest that at the time of their formation the climate was at

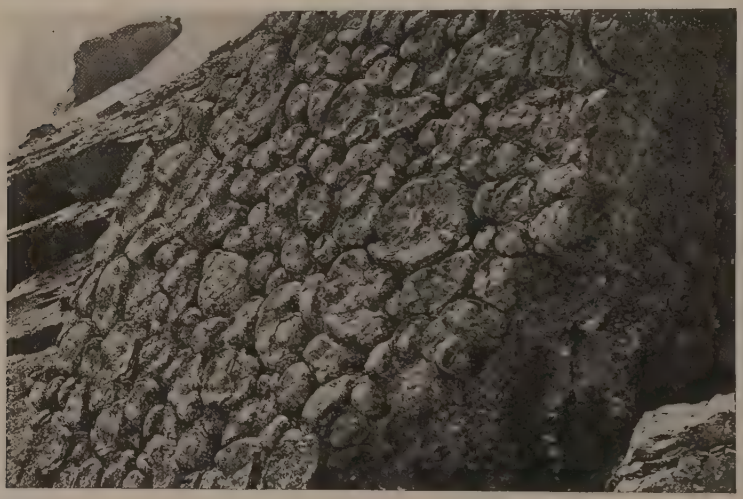


Fig. 360. — Proterozoic reef of calcareous algæ (*Collenia? frequens*), Flathead County, Montana. Photograph by Willis, U. S. Geol. Surv.

least mild. We may, therefore, conclude that at this very early time in the geologic history of the earth the climates were in general of the same nature as they have been ever since. That is, this and other evidence indicate that during long stretches of time the temperature of air and water was mild and fairly uniform the world over, but that at somewhat irregular intervals cold climates developed that were geologically of short duration. The times of reduced temperatures appear to coincide with the beginning or close of the eras.

Life of the Proterozoic

It is not so long since it was thought that the Proterozoic strata were devoid of recognizable fossils, but during the past fifteen years Walcott has described such from various places and Cayeux has secured undoubted Radiolaria (Fig. 330), and possibly Foraminifera (Fig. 328), from Brittany in France. A careful search among the Proterozoic flints would probably reveal more of these, and one through the limestones might yield undoubted Foraminifera and possibly other micro-organisms.

Fig. 361. — Single head of an alga (*Newlandia concentrica*), from the Belt series, Montana. $\times \frac{2}{3}$. After Walcott.

The most abundant fossils of the Proterozoic limestone strata are the secretions of *calcareous algæ* commonly known as *Cryptozoön* (Figs. 360–362). These coral-like plant masses make entire beds that repeat themselves time and again through thousands of feet of limestone; and,

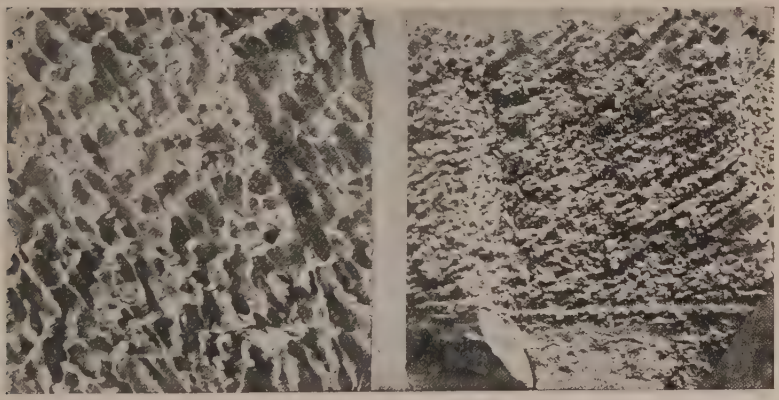


Fig. 362. — Internal structure of a Proterozoic alga (*Camasia spongiosa*), from the Belt series, Montana. About natural size. After Walcott.

while they may never be of value for detailed correlation, they will help toward establishing the zones of the Proterozoic.

Walcott has recently shown that certain of the Proterozoic (Belt) limestone formations abound in a variety of layered secretions due to the physiological processes of algæ (blue-green) living in water with lime salts in solution. One of

these forms has long been known as *Cryptozoön*. Walcott now describes them under six new genera and ten species. Most of them occur in abundance in the Newland limestone in Montana throughout a thickness of 2000 feet. Higher up come the Greyson shales, 3000 feet thick, with marine annelids, but without the algæ. Still higher are the Spokane shales, 1500 feet thick, and here again in a thick zone the algæ abound. We may, therefore, truthfully say that the Proterozoic strata of the Cordilleran region abound in fossils, but not in such forms as would be expected from the evidence of the Paleozoic formations. It is rather a plant world of the lowest type, that has left inorganic structures from which but little of the original organisms that caused their formation can now be learned. The progenitors of the Paleozoic marine faunas are still to be discovered.

A further interesting discovery was made by Lawson and Walcott in 1912 when they secured an abundance of fossils, probably also algæ (*Atikokania*), in a Huronian limestone over 500 feet thick at Steeprock Lake, west of Port Arthur, Ontario. These fossils are cylindrical or cornucopia-like to semiglobose bodies from 1 to

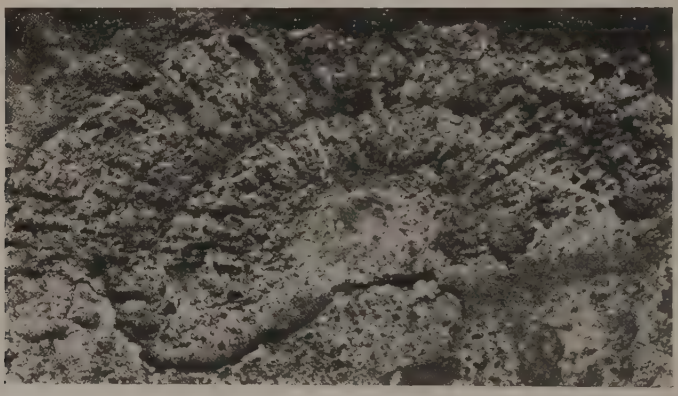


Fig. 363. — Weathered section through an alga (*Atikokania lawsoni*). × 2. Geol. Surv. Canada.

15 inches in diameter and height (Fig. 363). The solid structure is very thick and is traversed by an abundance of comparatively large radiating canals; in general it is like that of other Proterozoic algæ.

From the upper portion of the Proterozoic (Belt series) of Montana, Walcott has described a number of *worm burrows and trails*, seemingly of segmented annelids, that were found 7700 feet beneath the top of the section (Fig. 364). They are among the youngest fossils known in the Proterozoic, and even though they are only burrows and trails they seem to indicate the presence here of free (errant) annelids, a class of marine invertebrates high in the line

of organic evolution. There are still other fossils, but their nature is too obscure to make out their relationship to known organisms.

This evidence shows not only that life was present very early in the Proterozoic but that it had been existent for a long time previously, as proved by the calcareous algæ, marine plants that are, it is true, still primitive in organization and yet are greatly advanced over their more primitive progenitors. Finally, in the later

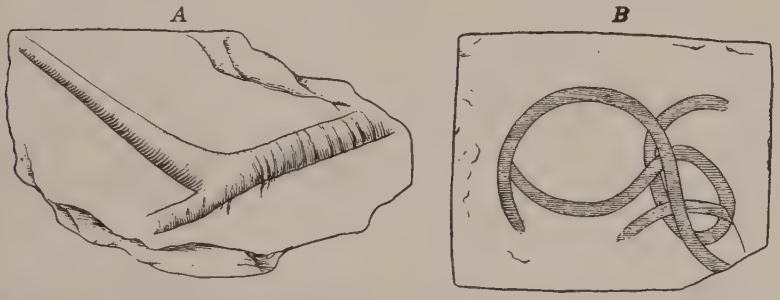


Fig. 364. — Burrows of Proterozoic worms. *A*, cast of large burrow (*Planolites corrugatus*). *B*, imprint of the actual annelid tube (*Helminthoidichnites meeki*). After Walcott.

Proterozoic, occur the Protozoa, a class of organisms represented by the Radiolaria, and here are also found Annelida. This means that most of the invertebrate classes of organisms other than the highest phylum (Arthropoda) were then in existence.

The above direct evidence of life in the Proterozoic also establishes the indirect testimony as to the abundance of organisms, even though lowly, which were necessary to have made the limestones, carbonaceous shales and iron-ores, not only of this era, but of the Archeozoic as well.

CHAPTER XXX

THE PALEOZOIC ERA

Comparison of the Paleozoic and Older Records. — With the beginning of Paleozoic time the strata are far less disturbed and have an abundance of fossils. Accordingly, there is at hand a ready and reliable means of correlating the formations not only from place to place but even between continents. Hence we have in most post-Proterozoic strata a far more detailed classification of the events, and also a greater knowledge of two parallel evolutions, that of the rocks and that of the organisms. As these two sets of phenomena are constantly interacting, they are checks upon each other in the determination of the actual events which happened at any time at a given place. In other words, because of the abundance of fossils in the Paleozoic and subsequent times, we have a ready means of deciphering a much more detailed history of the earth and its life than is the case in the earlier though far longer chronology.

North America: the Type Continent

Definition of Continent. — Dana long ago well said: "America is the type continent of the world." North America *is* the type continent, because of its simplicity of geologic structure, not only throughout its vast extent but also throughout the geologic ages. The other continent of the northern hemisphere, on the contrary, is more complex in structure, since only in the course of time, through the welding together of several land masses by orogenic (mountain-making) forces, has Eurasia been formed. A typical continent, Dana states, is "a body of land so large as to have the typical basin-like form, — that is, independent mountain chains on either side of a low interior."

Canadian Shield. — A great part of the northern half of North America comprises the Canadian Shield, described in foregoing chapters (see also Fig. 365). As we have seen, there is here revealed the greater part of pre-Cambrian history, events which took an immense lapse of time to accomplish, and the details of which will always remain far less clear than those of the southern half of the continent.

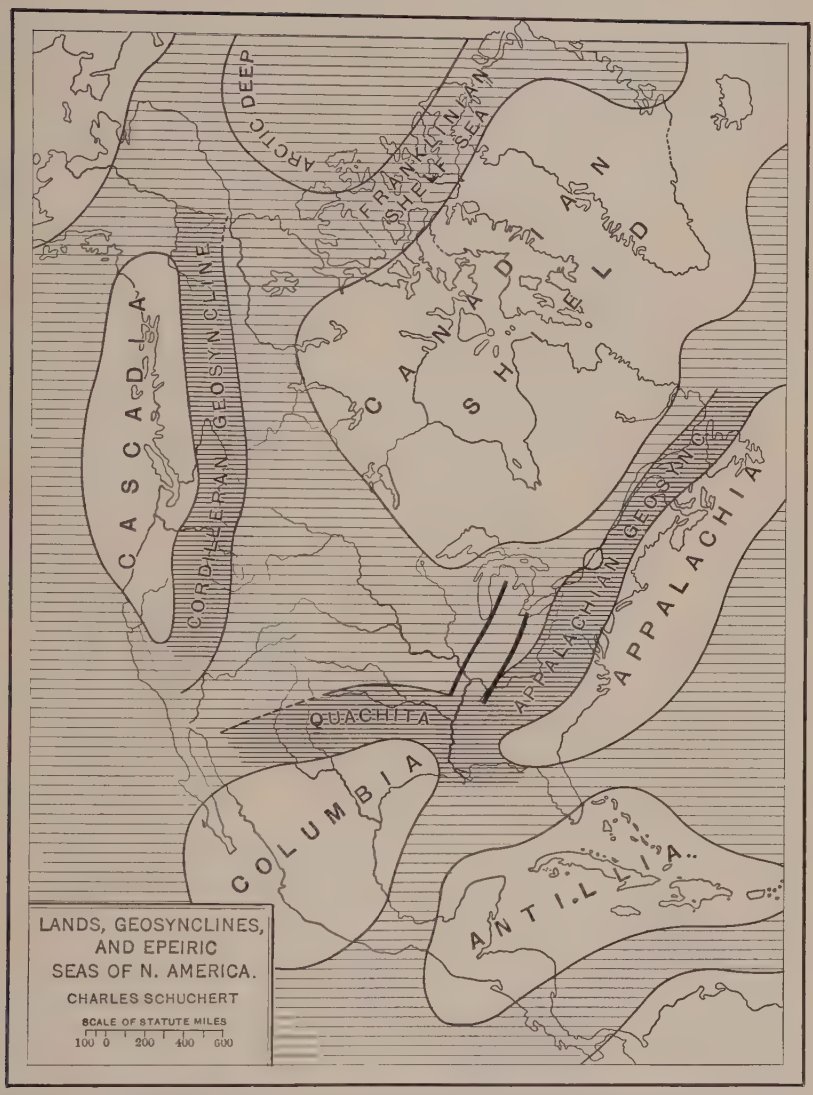


Fig. 365. — Generalized map of North America in Paleozoic time, showing in white the lands or positive elements, in darkest shading the three geosynclines or subpositive elements, and in lightest shading the extensive neutral medial area of the continent. The two heavy black lines indicate the Cincinnati and Ozark (Kankakee) uplifts.

Appalachia as here drawn is divisible into two geologic units; the northern half down to Long Island is known as Acadia, while the southern half constitutes Appalachia proper.

The surface exposures of the Paleozoic formations are shown on the Geological Map of North America at the end of this volume.

Depression Fields and Mountain Areas. — To the north, and more especially to the south and west of the shield, lie vast depression fields, or neutral and subpositive areas, which have tended through the geologic ages to lie slightly below sea-level. Because of this low level, the sea has often spread over these fields and recorded there the post-Proterozoic events.

To the east of the southern depressions occur the basal remnants of a mountain system, exposing a complex of metamorphic and igneous rocks and showing that again and again during geologic time majestic mountain ranges, studded at times with volcanoes, have been raised above the present basal structures. These mountains lay on the western side of Appalachia, the eastern shore of which has in the course of time sunk deeply into the abysses of the Atlantic Ocean (see page 357 and Figs. 282 and 365).

The western depression field is a very wide one, bordered on the west by another old land, Cascadia (see Fig. 365), which faced the Pacific. These regions were the scene of tremendous geologic activity, the struggle for dominance between the continent and the

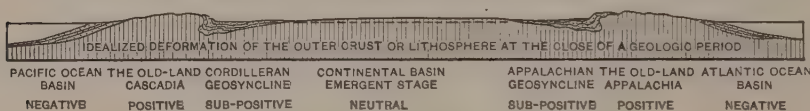


Fig. 366. — Diagrammatic cross-section through Fig. 365, at about lat. 38°, to show relation of continent to oceans at close of each period. Vertical scale greatly exaggerated. After Barrell.

Father of Oceans, in which the land was victorious, but only after building and rebuilding marginal bulwarks of chain upon chain of mountains, marked by volcanoes, from Alaska to Mexico City. The western region now embraces the grand Cordilleras.

We see, then, that North America has the form of an elongate basin, widely open at the north and nearly closed at the southeast; though in the latter place there stood for a long time a transverse mountain range, the Quachitas of Oklahoma, of which only the bases now remain, and these are in part concealed by later mantles of sediments. The geology of the Arctic shelf sea is not yet well known, but the sediments in the folded United States Mountains of Arctic America are of considerable thickness and extent. Between these elevated margins lies the great basin of North America, much of which has always been near sea-level (see Fig. 366), and over it, entering through the gaps between the marginal uplands, the oceanic waters have again and again flowed widely, to form interior shallow seas. These floods have come from the four quar-

ters, most widely from the Arctic and Pacific, least from the Atlantic, and most persistently from the American mediterranean. The partial deciphering of these multitudinous events in their orderly sequence, in addition to the similar unravellings in Eurasia by the geologists of that continent, has given the very imperfect geologic time-table presented in Chapter XX.

Paleozoic Era

Definition of Era. — We may define a geologic era as the longest division of time bounded by critical periods and characterized by comparative stability of the earth's crust and its organisms. Organic evolution was slow and pulsatory, with a tendency to specialization and adaptation among the plants and animals, during these more or less static times. The *intervals* of erosion bounding the eras were usually of long duration and the resulting unconformities are as a rule marked.

Definition of Paleozoic. — Upon the vastly thick masses of ancient igneous, sedimentary, and metamorphic rocks of Archeozoic and Proterozoic times, rest in marked unconformity the abundantly fossiliferous and as a rule little metamorphosed strata of the Paleozoic era. In the past century, geologists in general held that these rocks contained the evidences of the *first life* that appeared on the earth. Accordingly, Sedgwick in 1838 named the lower part the *Paleozoic series*, the name meaning *ancient life*, as he then believed it to contain the first life. Since then, however, as previously shown, fossils have been found in the Proterozoic, and it is now believed that low forms of life lived also in the Archeozoic. Nevertheless, the term Paleozoic is not only retained for the part defined by Sedgwick, but has been extended until it is now understood to embrace all of the time and rocks between the older Proterozoic era and the younger Mesozoic era. The Paleozoic is at present regarded as the third or fourth geologic era in the history of the earth, or the third or fourth chapter of the "book of geologic time."

Revolutions and Disturbances. — The Paleozoic is bounded below by the great Epi-Proterozoic interval, and is closed by the Appalachian Revolution (Dana), one of the most marked of the critical periods, beginning early in Pennsylvanian time and persisting during much of the Permian, when the Appalachian Mountains underwent their final upheaval. Between these two critical periods occurred other but less significant mountain-making ones, more especially toward the close of the Ordovician and Devonian,

thus dividing the Paleozoic era into Early, Middle, and Late sub-eras. The mountains then thrown up were, however, far less extensive than those at the close of the eras, and for this reason the times of their uplift are designated in this book as times of *disturbance*, to distinguish them from the times of revolutions or critical periods in the history of the earth.

Paleozoic Sub-eras. — A sub-era is a division of a geologic era. The sub-eras are bounded physically either by a revolution and a disturbance or by two disturbances, and organically by the dominance of a group or class of organisms. In the Paleozoic there are three of these sub-eras, as follows: (1) The *Early Paleozoic*, including the Cambrian and Ordovician periods, which is known as the *Age of Higher Invertebrates*, and which in a broad way may be said to be devoid of land plants and vertebrates; (2) The *Middle Paleozoic*, embracing the Silurian and Devonian periods, which is called the *Age of Fishes*, and which saw also the first land floras; (3) The *Late Paleozoic* or Carboniferous, including the Mississippian, Pennsylvanian and Permian periods, which has been termed the *Age of Amphibians* and of *Lycopods* (ancient seedless plants), and which was also the time of greatest coal-making, since then were laid down not only the best coals but the most extensive beds as well. (See geological time-table in Chapter XX.)

Division of Sub-eras. — The sub-eras are further subdivided into *periods of time* or *systems of rocks*. How this is done has already been explained in Chapter XX, but it will be well to take the matter up again in different form.

The older geologists divided the formations into systems on the basis of unconformities or marked differences in the entombed fossils. As the work proceeded and knowledge became more detailed, it grew increasingly difficult to formulate principles for the discrimination of natural periods and systems. For instance, when Murchison defined his Silurian system he divided it into an Upper Silurian and a Lower Silurian series on faunal grounds, although for a long time he was not aware of the angular unconformity between his divisions. In Bohemia, where Barrande worked a lifetime to unravel the very fossiliferous older Paleozoic, beginning in the Middle Cambrian and extending into the Middle Devonian, this geologist concluded that the entire series of strata was without "breaks," and called it all "The Silurian system," dividing it into the divisions *A* to *H*. Again, the New York State geologists of 1838–1842, in deciphering the splendid Paleozoic sequence of that state, concluded that they had throughout a conformable

series beginning in the Upper Cambrian and continuing unbroken into the Carboniferous. This sequence they called "The New York system," and separated it into five "divisions." According to more modern usage, there are here six periods, though the dividing lines of later geologists are very different from the original ones. The newer geology, however, seeks to divide the Paleozoic era in America into eleven or twelve periods.

In one form or another, geologists have always delimited their geologic divisions according to movements of the earth's crust, but how to discriminate the smaller movements from those that have more or less of a world-wide application for the delimitation of periods or systems is only now becoming clearer. Dependence will always have to be placed primarily on the fossils, but some criterion other than that of the contained life is needed to differentiate between the systems of stratified rocks. Such a physical principle apparently exists in the periodic submergences of the continents, also known as the positive changes of sea-level, for when one of the floods attains its maximum of spread, the widest distribution of similar faunas and identical species would naturally be expected. Conversely, the maximum of continental emergence must mark the absence of marine faunas in most land areas, followed for a time by more or less dissimilar faunas in all the provinces. The plotting of these periodic submergences and emergences on paleogeographic maps, not merely for one continent but for most of the world, will make it possible to define the boundaries of the systems of rocks and will also help greatly to determine a more accurate time valuation of the formations and their life in the various continents. It is, therefore, the principles of *diastrophism* and *paleogeography* that will eventually correctly define the periods or systems.

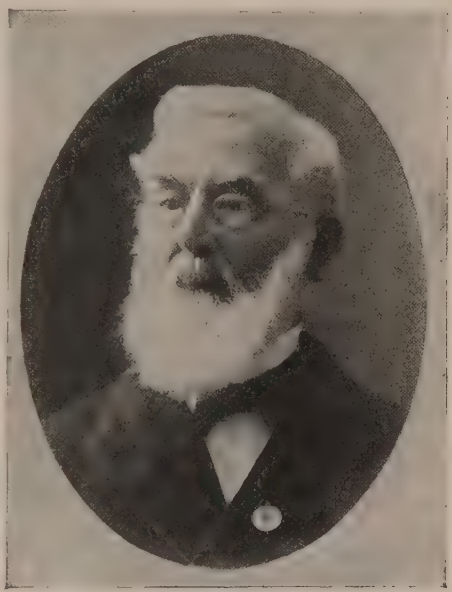


Fig. 367. — James Hall (1811–1898). Founder of the "New York system."

Definition of Period and System. — A period of time or a system of strata is a division of an era or sub-era and is bounded by breaks or intervals and loss of record other than that of erosion. The strata of each period record a marked submergence of some part of the continent and a marked emergence of the same area. The cycle of water movement may be connected with mountain making within the continent affected or elsewhere in a known or unknown continental or oceanic region. Therefore, the bounding unconformities may be of the non-conformable or disconformable type (see page 292), and when of the latter kind the organic record of the strata above and below alone may prove the delimitation.

Definition of Epoch and Series. — A period of time is very long, and a system of formations is usually of great thickness; in fact, these divisions embrace so many events that other and smaller groupings are required for their better comprehension. A period is therefore subdivided into *epochs* of time, and a system of formations is distributed into *series* of strata. In general, epochs and series are now rather arbitrary divisions established either on faunal grounds or on a long series of strata supposed to represent a sedimentary cycle, beginning in a conglomerate or sandstone and ending in calcareous deposits. While these criteria are more or less correct, they need to be checked by diastrophism and paleogeography. As a rule, however, it seems that each period has three epochs representing the early and late phases of small epeiric seas, and a middle phase of greatest periodic oceanic spreading. The epochs and series are further divided into *ages* (time) and *stages* (rocks), but these divisions have as yet no scientific precision.

Definition of Formation. — The word formation is used in different ways, and has come to be a general term embracing rocks alike or varying in character, origin, and thickness. According to Dana, it is applied to "any group in the series of stratified rocks, whether large or small, if the parts are related in period or time of origin"; as, for example, Devonian formation, or Chemung formation. He says further that "the term is also used for a group of rocks of similar constitution; as a calcareous formation, a siliceous formation." In general practice, however, formations are the smallest units that can be plotted on a geologic map, and may consist of a single more or less thick succession of like sediments, such as the Trenton limestone, Rochester shale, or Medina sandstone, or of a succession or alternation of sediments that are unlike (for example, shale, limestone, and sandstone), but have closely related faunas, such as the Hamilton formation. In short, any set of conformable strata grouped together for any stratigraphic or faunal reason or a number of reasons may be termed a formation. Where the formations are thin, as in the interior of North America, it often happens that several must be grouped together, so that

the geologist may be enabled to plot their outcrops on a geologic map. The Hunton formation of Oklahoma is a case of this kind, for it has four formations of Silurian and Devonian ages, which, in spite of their thinness, are separated by disconformities. Finally, the formations are combined into systems of rocks representing periods of time.

Old and New Divisions of the Paleozoic. — The divisions of the Paleozoic era are as follows (see also table in Chapter XX):

Sub-eras.	Recognized Periods.	Diastrophic Periods in America.
Late Paleozoic Age of Amphibians and Lycopods	Permian	Pennsylvanian
	Pennsylvanian	
	Mississippian	Tennesseian
		Waverlian
Middle Paleozoic Age of Fishes	Devonian	Devonian
	Silurian	Silurian
Early Paleozoic Age of Higher Invertebrates	Ordovician	Cincinnatian
		Champlainian
		Canadian
		Ozarkian
	Cambrian	Croixian
		Acadian
		Waucobian

Paleozoic of North America

Eastern North America. — Nowhere in the world may there be studied so complete a Paleozoic series of little deformed sedimentaries and one so replete in fossils as that of North America. For the distribution of these rocks see the geological map of North America in the pocket at the end of this book. To the north of the St. Lawrence River and the Great Lakes lies, as we have seen in Chapter XXVIII, the Canadian Shield or *nucleus of North America*,

a region composed essentially of Archeozoic and Proterozoic rocks. It was only during the early part of the Paleozoic that this nucleus was widely overflowed by the Arctic Ocean, and at no time during this era was its entire area under the sea, for nearly all of the shield east of Hudson Bay and south of Hudson Strait, that is, Ungava and Labrador, apparently has remained land at least since the close of the Proterozoic. It is around and in part over this ancient nucleus that the later Paleozoic sediments have been deposited, and in a general way it may be said that younger and younger strata are seen at the surface as one proceeds from the nucleus to the south and west and northward toward the Arctic Ocean. This statement, however, must not be taken too literally, for it will be shown that the Paleozoic sea invasions and the deposits of sediments in them were irregular in their extensions over the North American continent, and that most of these inundations lay to the south and west of the shield or *Laurentia*, as this very ancient nuclear land has been called by Dana and Williams.

Interior of North America. — Almost everywhere to the south of the St. Lawrence and Ottawa rivers and the Great Lakes, the Paleozoic strata are to be seen at the surface, extending over the wide watersheds of the Ohio, the northern half of the Mississippi and the eastern third of the Missouri rivers. The invading seas were shallow and laid down their deposits in practically horizontal and thin sheets, which even now over vast areas are not much deformed. Only in the narrow area of the Appalachian Mountains are the Paleozoic beds much folded and faulted, and here also occur the coarsest sediments and the greatest thicknesses. As one proceeds westward from this area, the folds are seen to flatten out gradually in the region of the Allegheny Mountains, and thence westward the undulations are so slight as not to be detected by the eye. However, there are also great sags here — shallow basins of rock that lie between belts of uplift. Two such basins are situated one on either side of the *Cincinnati uplift*, a low arch of strata beveled by erosion across its top, having the general trend of the Appalachians, and to be traced at the surface from Nashville, Tennessee, north of Cincinnati and then underground through the oil and gas regions of western Ohio and eastern Indiana (see Fig. 282 on page 357). It is this uplift with its nodes of older Paleozoic strata (Nashville and Cincinnati domes) that separates the eastern or Appalachian coal fields from the eastern interior coal basin of Indiana, Illinois, and western Kentucky. To the southwest of St. Louis, Missouri, lies a third extensive dome exposing older forma-

tions, the *Ozark uplift*, with another very extensive basin extending to the northwest, west, southwest, and south, and having as its youngest strata the western interior coal field (see Fig. 365).

Western North America. — This vast elevated interior country has the Paleozoic deposits covered in the south (Gulf area) and west (Great Plains country) by younger deposits, but in the far west in the folds of the Rocky Mountains the Paleozoic strata reappear at the surface. They are seen here in folded narrow bands and locally in basins from northwestern Mexico north to the Arctic Ocean, and from the Pacific states as far east as Denver, Colorado. The limited and often small outcroppings of these western Paleozoic formations are due to the repeated deformations and bevelings by erosion which they have undergone since their deposition. Further, they are so broken through and injected by igneous rocks of Mesozoic and Cenozoic age that a geologic map can show the outcrops only in a very limited way, although the Paleozoic seas had here an extension not much smaller than those of the eastern waters. Because of these inherent difficulties, the vast areas, and the scanty means of travel, the deciphering of the geologic history of the Rocky Mountains has not progressed beyond the preliminary stages. The student should, in this connection, study the geological map of North America to be found in the pocket at the end of the book.

Nature of Sediments. — The Paleozoic sediments in the Appalachian and Acadian areas are in the main a land waste, now transformed into shales and sandstones, with but little calcareous material, though limestones were laid down in Upper Cambrian and Ordovician times. In the Cordilleran sea, there was much sandstone and less shale, while the calcareous sediments were in the main of greatest thickness. Between these two bordering troughs or geosynclines of the continent the epeiric seas laid down thin sheets of sediments that, as a rule, are calcareous and include limestones, dolomites, calcareous shales and very little sandstone. In western Europe, on the contrary, the Paleozoic is characterized by the dominance of graywacke, that is, coarse detrital deposits of quartz-sand, feldspar, and mud, and by sandy slates derived from the older rocks. Because of the preponderance of the coarse deposits, the smaller seas of the European continent are believed to have lain between higher lands of ancient rocks and Paleozoic eruptives than was the case in North America, where it was only the Appalachian sea that was marked by this coarser sedimentation.

Imperfection of the Paleozoic Record. — Nowhere is there a complete record of Paleozoic formations, and even when the knowledge that has been gleaned from a study of all the North American exposures is pieced together, the record is still incomplete, though the gaps are not thought, as a rule, to represent long intervals of time. The longest array of superposed strata is to be seen in the Appalachians from northern Pennsylvania south to northern Alabama, and when the formations here are studied in detail, and widely separated places are compared with one another, it is found

Fig. 368. — Bear Grass limestone quarries, Louisville, Kentucky. The Devonian coral reef rests disconformably (at black line) on the Silurian coral reef.

that certain formations of one section may be greatly thickened or thinned or even completely absent in another (see Figs. 368, 369). Even the famous sequence in the state of New York, the "Standard Section" with which the Paleozoic strata of America are compared and correlated, is now known to be very much interrupted by breaks or intervals of erosion.

The imperfection of the geologic column is greatest in the interior of North America and more so in the north than in the south. This imperfection is in many places very marked, since an entire period or several periods may be absent. With such great breaks in the local sections the natural assumption is that these

gaps are easily seen in the sequence of strata, but in many places the beds lie in such perfect conformity upon one another that the breaks usually are not noticeable by the eye and can be proved to exist only by the entombed fossils on each side of a given bedding plane. This by no means exceptional condition of sedimentation is due to the fact that the interior sea invasions periodically flooded the low-lying continent from different directions and in varying depths, and to the further fact that the land was not folded but only warped from time to time, causing the epeiric seas to have varying extensions and outlines. In addition, there are more or less large areas that persist as lands, and these are called positive elements because the average of their movements in respect to sea-level or the strand-line is upward. They bound the interior seas or appear in them as low

Fig. 369. — Limestone exposure at Newsom, Tennessee. At the top are black shales of the Mississippian, resting disconformably on six feet of Middle Devonian, which in turn lies disconformably on the Middle Silurian.

islands. Stratigraphers are, as a rule, now fully aware of the imperfections in the geologic record, but the rocks of two unrelated formations may rest upon each other with such apparently absolute conformability as to be completely deceptive as to the great depositional break in the section studied. For instance, in the Bear Grass quarries at Louisville, Kentucky, a face of limestone is exposed in which the absolute conformability of the beds can be traced for nearly a mile, and yet within 5 feet of vertical thickness is found a Middle Silurian coral bed overlain by another coral zone of Middle Devonian time (Fig. 368). The parting between these two zones is like that between any two limestone beds, but this

insignificant line represents a stratigraphic hiatus the equivalent of the last third of Silurian and the first third of Devonian time. Such disconformities are by no means rare, in fact are very common throughout the wide central basin area of North America (Fig. 369).

Positive Continental Elements

Laurentia and Eria. — The largest, most ancient, and most persistent positive element is, of course, the nuclear area of northeastern North America previously described as Laurentia or Canadia, which is but the western end of a once far greater continent uniting North America and Greenland with the Euro-Asiatic masses and persisting throughout the Paleozoic and for a long time afterward. This land in its entirety is often referred to by geologists as the Great North Land, but Suess, following the older usage of Dawson, prefers to call it *Eria* (see Fig. 436).

Appalachia and Acadia. — Along the eastern side of North America are situated the far less extensive but also very ancient lands known as Acadia (Schuchert) and Appalachia (Dana) (see Fig. 365). The former embraces the New England States, the Canadian Maritime Provinces, southern Quebec and Newfoundland; as thus defined the land is seen to be far more extensive than the Acadia of the early French colonists, who applied the name to Nova Scotia, New Brunswick, and the neighboring islands. During much of Paleozoic time this land was locally and irregularly in movement, and therefore its different parts were variable in mass and boundary. In other words Acadia was moved and folded repeatedly and eventually was pushed far northwest upon Laurentia by the great crust movements of the Appalachian Revolution. Acadia was also the region of much volcanic activity.

Appalachia embraces all of the United States east of the Appalachian Mountains from New Jersey to Florida, and appears to have been nearly devoid of volcanic activity since the beginning of Paleozoic time. However, as all of the ancient land has since been deeply eroded and in large part buried by younger strata, we really do not know to what extent igneous activity prevailed upon it. Moreover, how far these eastern Paleozoic lands extended into the Atlantic Ocean is unknown, but Appalachia certainly extended far beyond the edge of the present continental shelf (Fig. 365).

Cascadia (from the Cascade Mountains of Oregon and Washington). — Along the western border of North America, extending from northern Nevada and California through British Columbia

into Alaska, is an immense area with almost no Paleozoic sediments excepting along the extreme eastern and western borders. This appears to have been a positive element since the earliest Paleozoic and has furnished most of the land waste for the sediments of the Cordilleran sea situated to the east of it (Fig. 365).

Other Positive Elements. — In the southwest, most of Mexico was land throughout the Paleozoic, and this element will be referred to as *Columbia,* the land of the followers of Columbus. The greater Antilles were then united into a continental mass and as such have been called *Antillia* (Fig. 365). Among the much smaller positive elements, which were nevertheless significant as islands in the epeiric seas, the most important is the Cincinnati uplift, the northern portion of which is known as *Cincinnati Island* and the southern as *Tennessee Island.* These islands did not appear as such until Middle Ordovician time, but from the Silurian on were a marked geographic feature of the eastern inland sea. *Missouri Island,* or *Ozarkia,* the Ozark Mountains area of Missouri and Arkansas, was even more persistent than were those of the Cincinnati uplift.

Subpositive Continental Elements

Seas. — The inland or epeiric seas spread between the above defined positive elements, and as the areas of these waters were also more or less subsiding ones, they are referred to as subpositive and neutral continental elements (Fig. 366). These shallow epeiric seas may be characterized as follows: The *Central Interior sea* (Mississippian sea of authors) occupied variably at different times the drainage basin of the Mississippi River, from the Appalachian Mountains west to the eastern edge of the Great Plains and north from the Gulf of Mexico into the Hudson Bay depression. It was a Paleozoic epeiric sea and was divided into an eastern and a western part situated respectively on either side of the Cincinnati uplift. The extreme eastern part of the Central Interior sea will often be referred to as the *Appalachian trough* or geosyncline; it was the chief subsiding area of the Central Interior sea, forming a variably narrow trough immediately to the west of Appalachia proper and extending from eastern New York into Alabama (see Fig. 365), where its deposits pass beneath subsequent rocks. More than 30,000 feet of sediments were laid down in this geosyncline in eastern Pennsylvania, with smaller thicknesses to the north and south. The life of this sea was chiefly derived from the south or Gulf of Mexico and secondarily from the northeast or Gulf of St. Lawrence, but at

times also from the Pacific and Arctic. Another trough lay in the south and is known as the Quachita geosyncline. The *Cordilleran sea* occupied the area of the Rocky Mountain geosyncline and the Great Plains, and at times extended from Mexico into the Arctic Ocean. It was often in connection with the Central Interior sea, but its life came in the main from the Pacific and less often from the Arctic.

In the preceding paragraphs some of the positive and subpositive continental elements have been defined. Both are parts of the emerging continents, while the negative elements are the subsiding oceanic areas. It should, however, be understood that while the sum total of the continental movements in relation to the water level is upward, and in the same way the average of the oceanic bottoms is downward, nevertheless parts of the continents have gone permanently under the ocean, while parts of the oceanic areas have been added to the continents. This is explained in more detail in Chapter XXI.

CHAPTER XXXI

CAMBRIAN TIME AND THE DOMINANCE OF THE TRILOBITES

Cambrian in General

Origin of the Term Cambrian. — The Cambrian period of time or system of rocks takes its name from Cambria, the Roman name of northern Wales, where the deposits were first studied by Professor Sedgwick of Cambridge University in 1833. The term, however, was intended to apply to what is now called the Ordovician period, the one following the Cambrian, and although Sedgwick often objected to the transposition, brought about in the main by his friend Sir Roderick Impey Murchison, this misapplied usage has unfortunately persisted. On the other hand, it now appears that the formations heretofore embraced under the term Cambrian are not of a single period, but may be grouped into three periods, and for this reason the terminology is not yet finally established. To keep this matter clearly before the student, the accepted classification is retained for convenience, while the new arrangement is presented in the form of three *series* of formations, — Lower Cambrian or Waucobian time, Middle Cambrian or Acadian time, and Upper Cambrian or Croixian time.

Marked Unconformity at the Base of the Paleozoic. — In most places where the Cambrian or any later portion of the Paleozoic sedimentaries rests on the older Proterozoic or Archeozoic rocks, a marked unconformity is seen to be present between the strata. This unconformity is more pronounced and of wider extent than any subsequent one, though there are some localities, for instance, in western Montana and southern British Columbia, where the Paleozoic strata rest without marked unconformity (disconformity) on the earlier formations of Proterozoic time.

Cambrian Life. — The Cambrian period is the first one in the Paleozoic era. It is also the first one in the history of the earth with an abundance of life preserved as fossils. This animal life, which consists entirely of invertebrates, contains representatives of all of the more fundamental types, ranging from simple sponges to complex forms of Crustacea. The common animals are almost wholly trilobites (crab-like animals fully described in the next

chapter) and brachiopods (bivalved animals described in Chapter XXXIII), and as the former are characteristic of the Cambrian we speak of them as the dominant animals. See Pls. 1 and 2.

In the Lower and Middle Cambrian the external skeletons of animals were commonly made up of a substance containing some nitrogen (chitin and phosphate of lime), but subsequently thick-shelled molluscs and brachiopods with shells composed of carbonate of lime appeared in ever greater quantity and variety. It is estimated that about five hundred species of Cambrian invertebrate animals have been described from North America alone. From all countries together there are known fully one thousand species, about two thirds of which are trilobites and brachiopods.

Absence of all Land Plants. — Not the slightest evidence of a positive kind exists showing the presence of a land flora in Cambrian time, and the same statement is applicable to the greater part of the succeeding Ordovician. When, however, we consider that only the lower types of land plants could then have existed and that these were soft and nearly devoid of woody material, the only preservable portion, there is nothing extraordinary in this extreme imperfection of the plant record. The bottom-living plants of the sea, the *seaweeds*, are also very perishable and few of them are known as fossils; even in sediments of the finest sort, where one might expect to find them, they are very rarely preserved, and then only as impressions. Therefore, land plants do not occur in the geologic record until the woody ones appeared, and none of these latter are known earlier than late Ordovician time.

Cambrian Climates. — From the very wide distribution of the reef-making corals in Lower Cambrian times, as stated on a subsequent page, it is evident that the waters were warm and equable over most of the earth, since these animals lived not only in the present temperate regions but also in both polar areas. The wide occurrence of limestone-depositing seas in Middle Cambrian time, and more especially in the Upper Cambrian, with an abundance of varied life, is further evidence of mild climates all over the world probably throughout Cambrian time.

Significance of Cambrian Seas. — From the paleogeographic maps (Pl. 3) and the description of the Cambrian seas it will be seen that all of these waters and their stratified rocks lay upon the continent of North America between the bordering lands from which the sediments came. In other words, they were epeiric seas, and not marginal overfloodings of the continental shelves by the oceans (shelf seas), as is the case with the present Atlantic and Pacific

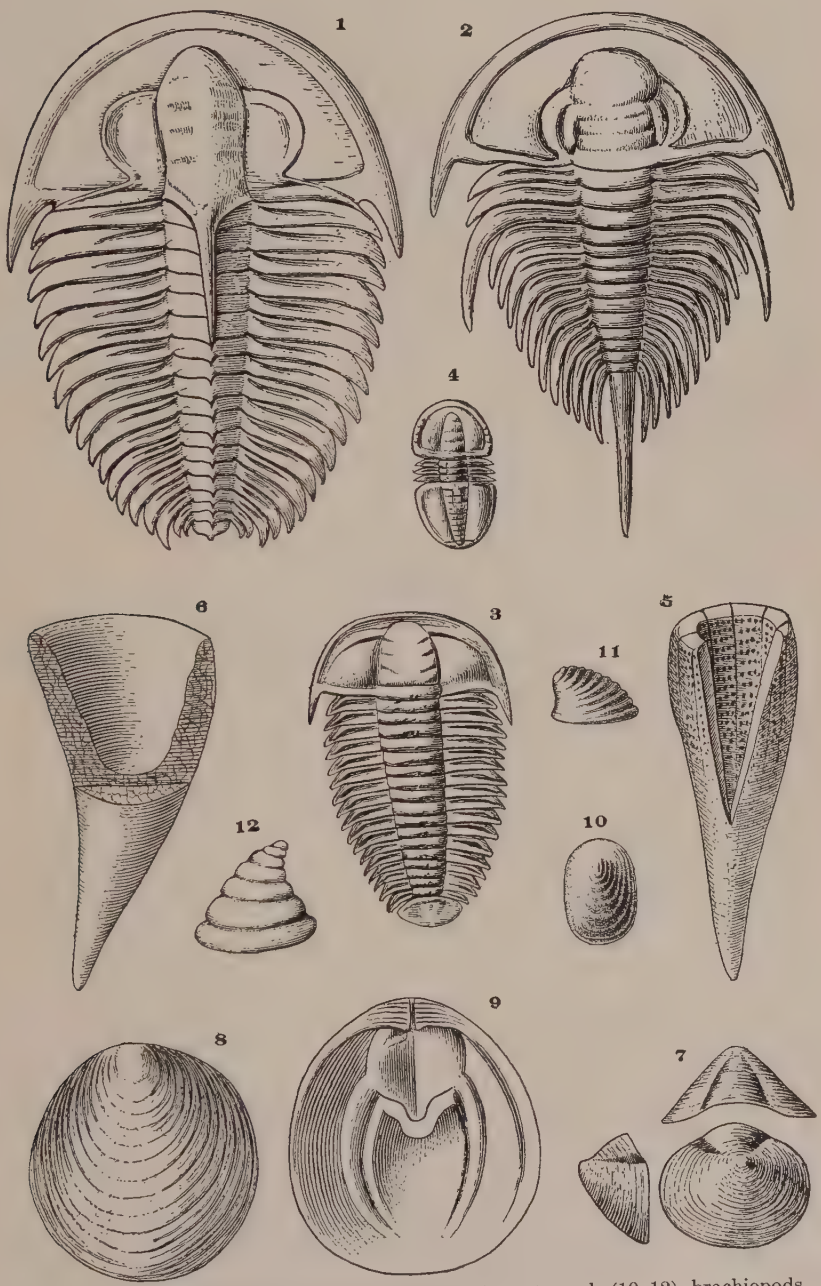


Plate 1. — Lower Cambrian trilobites (Figs. 1–4), gastropods (10–12), brachiopods (7–9), and corals (5, 6). See Appendix B.

oceans. If the present oceans are more than full and hence overflow more or less extensively the continental shelves, then the oceans of Cambrian time were in a far greater flood condition. The continents at present stand higher above the oceanic strand-line than was the rule in geologic history, and throughout Paleozoic time North America stood considerably lower relatively to this line, possibly 200 to 300 feet throughout the Mississippi drainage area. That the oceanic level is not a constant one is well attested by geologic history, but that it has been in ebb and flow to such an extent as is shown in the paleogeographic maps presented in this book has only become clear during the past few years.

Leading Cambrian Workers. — Our first accurate knowledge of Cambrian life was obtained in Bohemia through the great industry of a Frenchman, Joachim Barrande, who spent the greater part of his life as an exile at Prague. The complete stratigraphic succession of this period was first determined by the splendid work of Swedish geologists, while the American succession and faunas have been developed almost entirely by Walcott.

Lower Cambrian or Waucobian Time

The Lower Cambrian was made known by Walcott many years ago, but it was only in 1912 that he proposed the term Waucobian for these rocks, taking the name from Waucoba Springs, Inyo County, California, where the system has a thickness of not less than 5670 feet.

Waucobian Seas. — The paleogeographic maps of the probable seaways of Cambrian time are shown on Pl. 3. From them it is seen that the Pacific Ocean in earliest Lower Cambrian time first invaded the land in the Great Basin area and gradually spread northward, forming throughout the Cordilleran geosyncline a sea which finally united with the Arctic Ocean. Some time after the appearance of the western Cordilleran sea, a similar waterway developed to the west of Acadia and Appalachia, finally extending as a narrow trough — the Appalachian geosyncline — from Alabama to southeastern Labrador. At its maximum this inundation did not submerge more than 18 per cent of North America. It is not known where these waterways intercommunicated, but the entombed life of their deposits makes it clear that they had such a connection, for some of the species are common to these two widely separated seas, and, what is more important, the faunas of both regions have a general likeness. This is true not only for North America, but also for the whole northern hemisphere, indicating that the oceans were then openly connected with

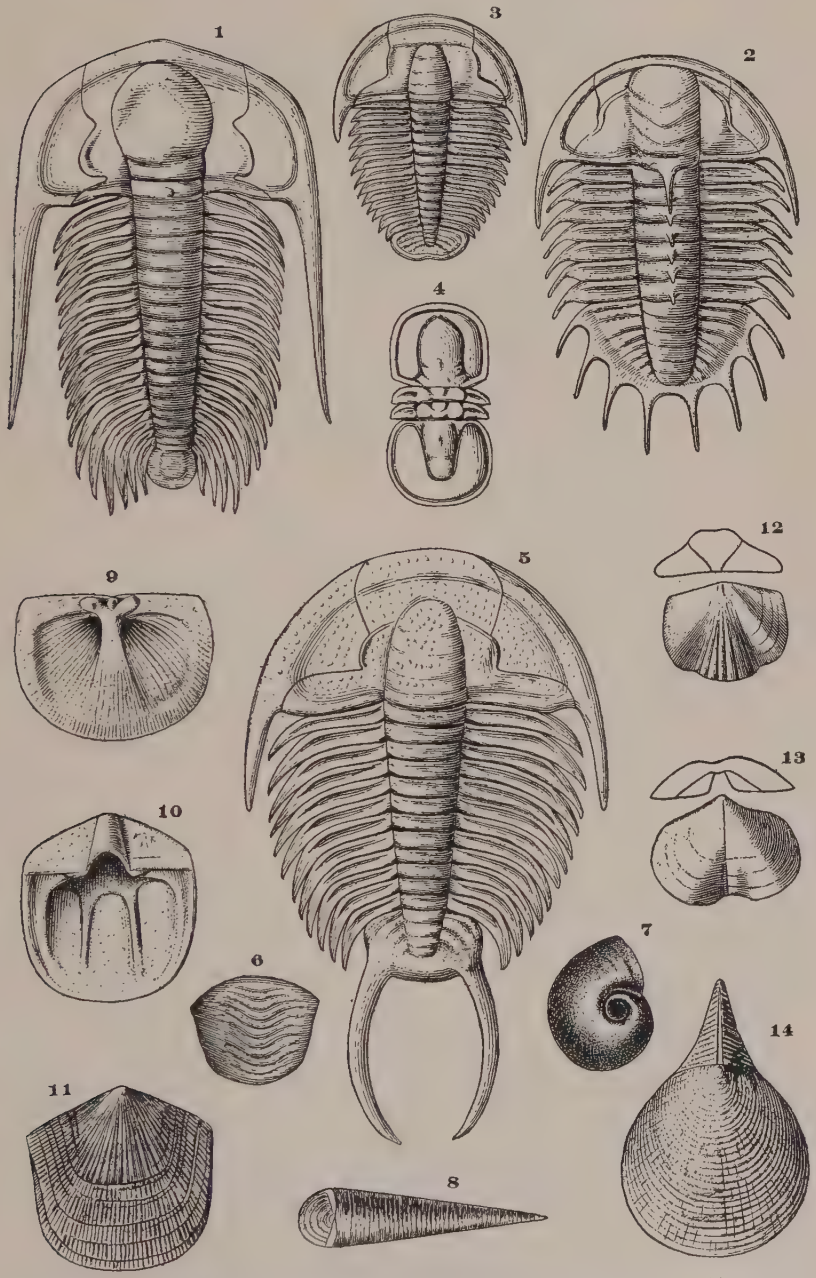


Plate 2. — Middle and Upper Cambrian trilobites (1–5), gastropods (6, 7), pteropod (8), and brachiopods (9–14). See Appendix B.

one another. It is therefore said that the life of the Lower Cambrian was *cosmopolitan* in character because the same, or nearly the same, kinds of fossils occur in all the known areas.

Waucobian Formations. — In the Cordilleran sea the Lower Cambrian had by far the best development. Here Walcott has measured sections of strata ranging from 1500 to 5670 feet in thickness. The material is usually sandstones or quartzites and was almost all derived from Cascadia, the bordering land on the west.

In the Appalachian trough and sea the Lower Cambrian thicknesses in places are also very great. In Vermont and northeastern New York there appear to be about 5000 feet, mainly of slate and sandstone, with an additional 1000 feet of limestone at the base. This material was very largely derived from Acadia and but little from Laurentia, which had remained a low flat land since its peneplanation in Proterozoic time. In eastern Pennsylvania, western Maryland and Virginia there are 1000 feet of limestone at the top with 4700 feet of sandstone and snale. A very similar thickness occurs in Tennessee, Georgia, and Alabama. All of the coarse materials came from Appalachia.

First Abundance of Fossils. — The life of the Lower Cambrian is particularly interesting because it is the first or oldest life of which we have a good knowledge, and its leading features must therefore be described. In the oldest of these deposits in California and Nevada, fossils are scarce and all that have been found are two forms of trilobites. Near the top of the Lower Cambrian, fossils are, however, abundant and consist of trilobites, snail shells, brachiopods, and very primitive stony corals (*Archæocyathidæ*), which also remind one of certain sponges (Pl. 1). In Inyo County, California, occur limestone reefs made up of such corals, the oldest ones known. These fossils occur in many parts of the world: Labrador, with reef limestones up to 50 feet thick; New Siberia, in 70° north latitude; Sardinia; Spain; Australia, with limestones fully 200 feet thick; and finally in Antarctica, as reported by Shackleton. (For further remarks, see Chapter XXXV.) The trilobites were the most characteristic animals of the Lower Cambrian. Nearly all of the brachiopods of this period had shells made of phosphate of lime, while those of the Upper Cambrian and later periods were of carbonate of lime. The gastropods (shells like the snails, drills, and periwinkles) were rare and of the most primitive type; with one exception, they were hood-shaped and not spirally coiled as is usually the case among these animals (Pl. 1, Figs. 10–12). The conical three-sided tubes known as *Hyolithes* were abundant (Pl. 2, Fig. 8). There were still other types of animals, but no bivalved molluscs (mussels) or cephalopod (nautilids).

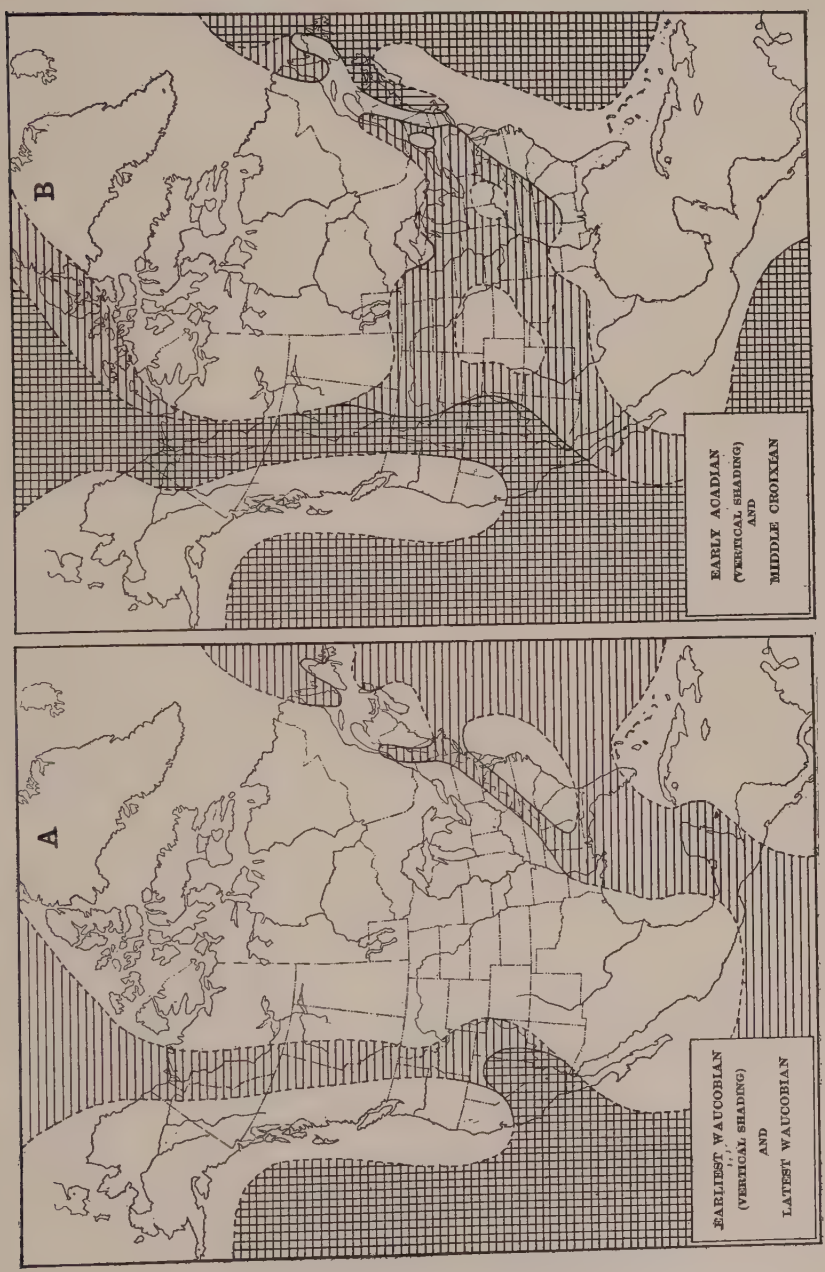


Plate 3. — Lower (A), and Middle and Upper (B) Cambrian paleogeography.

Characteristic Fossils of the Waucobian. — The Lower Cambrian in America is divisible into four faunal zones. The oldest one — Nevadia zone — is restricted to the Cordilleran trough, but the other three — Elliptocephala zone, Callavia zone, Olenellus zone — are common to this and the Appalachian trough.

The more characteristic fossils are as follows: of trilobites, *Olenellus*, *Mesonacis*, *Elliptocephala*, *Callavia*, *Nevadia*, *Atops*, and *Eodiscus;* among the gastropods, *Stenotheca* and *Scenella;* among the brachiopods, *Paterina*, *Kutorgina*, *Mickwitzia*, and *Obolella;* and of the corals, the Archæocyathidæ.

Significance of Lower Cambrian Life. — As trilobites, which belong to the highest division of invertebrate animals and are therefore really complex organisms, were the dominant life of the Lower Cambrian, it is plain that life could not have originated in this time. Even though it is now established that a variety of animals was present in the Proterozoic, still the change in the life of the Lower Cambrian, as compared with that of the former epoch, is very remarkable. We have seen that in the Proterozoic there were almost no organisms other than lime-secreting seaweeds and worm tubes, yet in the Lower Cambrian there was an abundance of very varied and highly complex animals. These facts mean that there is a very great loss of record in the geologic column between the latest Proterozoic and the oldest Cambrian deposits, the further significance of which has been discussed in the preceding chapter (page 569).

Green Mountains Disturbance. — Toward the close of the Lower Cambrian, both the Cordilleran and Appalachian geosynclines appear to have been drained of all or most of their marine waters, and a long time ensued before another cycle of marine invasion took place. In the meantime, life was evolving on the continental shelves, areas not now accessible to us for geologic study, and when the floods reappeared in the geosynclines they spread faunas that were unlike the previous one. This record of organic change during the interval of sea withdrawal is missing everywhere between the youngest Lower Cambrian and the oldest Middle Cambrian deposits, no transition faunas being yet known. Stratigraphers are now taking advantage of facts of this kind as a basis for distinguishing the periods one from another, and thus classifying them, as previously discussed.

This absence of epeiric seas in the Appalachian and Cordilleran troughs means that either one or more of the outer ocean basins had been deepened, thus withdrawing their waters from the geosynclines. Further, Walcott has shown that at the close of Lower Cambrian time the lands to the east of the Appalachian geosyn-

cline were elevated into a low ridge or barrier, which apparently extended from Newfoundland certainly to Connecticut and possibly into Alabama. It was this ridge that prevented the western or Pacific waters of the Cordilleran sea during Upper Cambrian time from mixing their faunas with those of the northern Atlantic Ocean (Poseidon), which lay to the east of the ridge or land. For easy reference the movement which brought about this uplift may be known as the *Green Mountains Disturbance*, since the Green Mountains of Vermont are now situated on the western border of the elevated area.

Middle Cambrian or Acadian Time

The sequence of the strata of this period and the faunas contained therein were first developed by G. F. Matthew from the region about St. John, New Brunswick, a part of the Acadian country, hence the name Acadian, proposed by James D. Dana in 1874. During Middle Cambrian time the Cordilleran sea had about the same limited geographic extent as that of the Lower Cambrian, while the Appalachian geosyncline appears to have remained continuously above sea-level.

Sediments. — In the Cordilleran sea the sediments of Middle Cambrian time were essentially thick- and thin-bedded limestones with but little shale. The thicknesses vary between 3000 feet in Nevada and 8300 feet in the Robson district of Alberta, Canada. In the Grand Canyon of the Colorado there are less than 1200 feet of sandstones and shales (see Pl. 3, Fig. B).

Acadian Faunas of the Cordilleran Sea. — The life of the Cordilleran sea was distinctly of the Pacific realm, very similar faunas being known in China. Trilobites were still dominant, and there was a greater variety of these interesting animals (Pl. 2, Figs. 2–4) than in the preceding epoch. The brachiopods were far more numerous, but still small, and almost all of them not only had phosphatic shells but were very similar to those of the Lower Cambrian.

The fauna of the Cordilleran trough is marked by the trilobites *Olenoides*, *Dorypyge*, *Neolenus*, *Ogygopsis*, *Asaphiscus*, *Bathyuriscus*, and *Agnostus*, and by the brachiopods *Micromitra*, *Acrothele*, and *Nisusia*. A very extraordinary and varied fauna represented by over ninety genera has been described by Walcott from the black Burgess shale found on Mt. Stephen in British Columbia, where this zone is but a few feet in thickness. The fossils are essentially crustaceans, with phyllopods, worms and sponges prominent. Other forms are medusæ (jelly-fish), pelagic and bottom-living holothurians, brachiopods, and Hyolithes with pteropod-like wings (see Pl. 2, Fig. 8). The finding of this fauna has re-

vealed a host of unsuspected animals, and furnished a good illustration of the great variety of life that lived in these early times; it is a revelation of how very imperfect our knowledge must be of any geologic age.

Acadian Faunas of the Atlantic Area. — In the Acadian region and in Newfoundland, there are other Middle Cambrian deposits, here essentially muds and sands, with distinctly different fossils, though of the same general faunal development as those of western Europe, in other words, of the Atlantic province (Pl. 2, Fig. 1). Hence the world no longer had a cosmopolitan fauna, but there were at least two distinct evolutionary areas whose respective dispersal centers were the Pacific and Atlantic oceans.

Close of the Middle Cambrian. — In all places where the Upper Cambrian strata repose on those of Middle Cambrian time it is seen that the life of the one series is sharply distinguished from that of the other; in other words, there are no known transition faunas of this time in America preserving the stages of evolving forms, and this is thought to indicate a break in deposition and an absence of faunal record. Only in the Cordilleran trough is there a possibility that the transition faunas may be recovered, for as yet we know little of its geology; in the Appalachian geosyncline the Upper Cambrian rests on the Lower Cambrian with all of the Middle Cambrian absent. This is evidence that in the latter region the elevation brought about by the Green Mountains Disturbance had not yet been overcome by erosion. However, there are so far no data showing that either Appalachia or Cascadia had been further elevated at the close of Middle Cambrian time. The subtraction of the oceanic waters at this time appears to have been due to crustal movements elsewhere than in North America, probably in the deep ocean basins, as previously suggested.

Upper Cambrian or Croixian Time

In Upper Cambrian or Croixian time (from the St. Croix River of Wisconsin, where these strata are well developed and fossiliferous), the seaways not only reoccupied the Cordilleran and Appalachian troughs, but the waters for the first time in the Paleozoic spread widely over the continent, occupying much of what is now the Mississippi basin. When the flood was at its widest, it covered more than 31 per cent of North America (Pl. 3, Fig. B). In general, the deposits are limestones, dolomites, and calcareous shales, with the minimum amount of sandstones.

Sediments. — In the northern part of the Central Interior sea the deposits are mostly sandstones, with a thickness in Wisconsin of about 720 feet. They are the residual materials or the loose rock and soil (regolith) of a long period of erosion and have been brought from Laurentia and the Adirondacks. These sands in small amount reached as far as the Ozark region of southern Missouri, where the Upper Cambrian deposits are thin and consist mainly of limestone and dolomite. On the other hand, in the Arbuckle Mountains of Oklahoma there are no less than 3000 feet of pure limestones and dolomites.

The Appalachian trough is another area of thick sediments of this age, nearly all of which consist of magnesian limestones with some shale. In Alabama the thickness is about 4000 feet, and this depth remains fairly constant all the way north to Chambersburg and Mercersburg, Pennsylvania.

The deposits in the Cordilleran trough are also essentially calcareous, with an average thickness of over 3000 feet.

Establishment of the Lime-secreting Habit. — The epeiric seas of Middle and Upper Cambrian time deposited a very great amount of rocks consisting of carbonate of lime; this means not only that the waters were clean of muds but that their temperature was warm as well. Life was more prolific in the Upper Cambrian and there was also an abundance of invertebrate animals with lime carbonate skeletons. In other words, for the first time in the history of the earth there was an abundant molluscan fauna, and the greater abundance of carbonate of lime in the seas established the lime-secreting habit permanently in many classes of animals. The trilobites, although less varied than before, were still abundant (Pl. 2, Fig. 5), while the brachiopods with phosphate of lime shells were now at the height of their development, and those forms having valves of carbonate of lime (Pl. 2, Figs. 9–13) were rapidly increasing. Then there were also a number of coiled and spiral gastropods (Pl. 2, Figs. 6, 7), and a few cephalopods of the pearly nautilus type as well.

Characteristic Fossils of the Croixian. — The more characteristic trilobites of the Central Interior sea and of the Cordilleran trough were *Dikellocephalus*, *Saukia*, *Illænurus*, *Conaspis*, and *Crepicephalus*. The earliest limulid (horseshoe crab) is present in *Aglaspis* and a eurypterid in *Strabops*. Of brachiopods there were *Linnarssonella*, *Lingulepis*, *Obolus*, *Syntrophia*, and *Billingsella;* of gastropods, *Owenella*, *Holopea*, and *Pleurotomaria*-like forms.

Close of the Upper Cambrian. — At present it is impossible to define the closing events of the Cambrian because of a difference of opinion among paleontologists as to the age of the formations usually accepted as the last members of the Upper Cambrian. The matter is set forth below. In any event, there was no mountain making at this time in North America. Apparently the closing

epoch of the Upper Cambrian was a time of quiet emergence and withdrawal of the sea.

Ozarkian

In 1911, Ulrich proposed the name "Ozarkian system" for a series of formations that had been referred mainly to the Cambrian and in part to the Ordovician. His definition of the new system includes all the formations in the Appalachian valley that can be shown to be younger than the top of the Upper Cambrian Nolichucky shale in eastern Tennessee and older than the base of the Beekmantown limestone as developed in southern and central Pennsylvania. The name is taken from the Ozark uplift in southern Missouri where the Ozarkian begins with a massive limestone known as the Potosi dolomite. The upper limit there included two Missouri formations, the Roubidoux and Jefferson City, which he subsequently referred to the Canadian period of the Ordovician.

At present, then, Ulrich begins the Ozarkian in Missouri, as in 1911, with the Potosi, but now closes it with the Gasconade. In the Adirondack area of New York, the Potsdam, Hoyt (Theresa), and the greater part of the Little Falls are regarded as of early Ozarkian time, but until Ulrich's evidence is fully presented, Walcott (1914) thinks it well to leave the two lower formations (= Saratogan) in the Upper Cambrian. In the upper Mississippi valley, Ulrich and Walcott both include the Mendota, Madison, and Oneota in the Ozarkian. In the southern Appalachian area, Ulrich refers the Nolichucky to the Cambrian, and begins the Ozarkian, as in 1911, with the Briarfield and Ketona, continuing upward into the Copper Ridge, and closing with the Chepultepec. In Pennsylvania, the Ozarkian is represented by thick formations of limestone, dolomite, and sandstone comprised in the Kittatinny, Conococheague, and corresponding formations.

Ozarkian strata are best developed in the southern Appalachians, with more than 4000 feet of dolomite in eastern Tennessee and 2500 feet of still older magnesian limestones in central Alabama. The total thickness may even attain 9000 feet.

The early Ozarkian sea invaded the Mississippi valley as far north as southern Wisconsin, spreading at the same time into the southern extremity of the Appalachian valley. The Atlantic also invaded the middle Appalachian valley about this time. Middle and later Ozarkian seas seem to have come in exclusively from the south, persisting a long time in the southern Appalachian and Ozark areas and spreading finally into Pennsylvania and New

York in the east, and through the upper Mississippi valley in the west.

As a rule, fossils are scarce throughout the Ozarkian, although locally they may abound in undescribed species. The most prevalent ones in a fauna of about two hundred forms are several species of calcareous seaweeds (*Cryptozoön*). A few brachiopods and more trilobites, most of them closely allied to Upper Cambrian species, are commonly associated with numerous gastropods and cephalopods having decided Ordovician affinities.

CHAPTER XXXII

TRILOBITES

History. — Trilobites were the first fossils to attract the attention of naturalists and have long been of popular interest. It was Lhywd, the curator of the Ashmolean Museum at Oxford, England, who, in 1698, first called attention to an entire specimen. He did not know how to classify it but thought it was the skeleton of an unknown fish, and for a long time the animals were regarded as beetle wings, caterpillars, insects without wings, fossil butterflies, and even molluscs. The great Swedish naturalist, Linnæus, first correctly recognized their relationship with the Crustacea, animals such as shrimps, crabs, and lobsters. Professor Walch of Jena, Germany, in 1771, gave them the generic name *Trilobites*, a term that has since been raised to the rank of a subclass *Trilobita* of the class Crustacea of the phylum Arthropoda, which contains an exceedingly varied array of animals with articulate or segmented bodies and limbs, among them the crustaceans, insects, scorpions and spiders. There are now about two thousand kinds of trilobites known (see Pls. 1, 2, 6, 9, 18).

Definition. — The word trilobite means *three-lobe-like*, and has reference to the three longitudinal lobes (the central *axis* and lateral *pleura*) seen on the dorsal or upper side of most trilobites (see Fig. 370). They were sexed animals. Their bodies were made up of segments, many of which articulated upon one another; and these segments were gathered together into three divisions, as may be seen in any entire specimen of the upper shell or *carapace*, the part usually preserved. The under, or ventral, side with the limbs had a very thin outer shell and was preserved only in exceptional conditions, usually in black, more or less sulphurous shales. The carapace was thin, and made up of chitin (very much as in horn, hair, etc.), a nitrogenous substance to which is added more or less of lime salts. Chitin greatly resists chemical alteration, and this is the reason why trilobites are so often preserved as fossils.

Habitat. — Trilobites inhabited only marine, and in the main, shallow, waters, and their tests or outer shells are found in all

kinds of marine sediments, but chiefly in shales and limestones. Most of them were good swimmers, some crawled over the bottom, while others lived partly buried in the muds. They were *characteristic of the Paleozoic era*, beginning in great variety in the Lower Cambrian and dominating the seas of Cambrian (55 genera and 300 species) and Ordovician time (80 + 950). In the Silurian, though they were still common, the trilobites were nevertheless on the decline (30 + 485), and this ebbing of their vital force is seemingly shown in many picturesque forms replete with protuberances, spines, and exaggeration of parts. As a rule, in evolution, one finds that when an organic stock is losing its vital force there arises in it an exaggeration of parts, as if heroic efforts were being made to maintain the race. Spinosity in animals is often the prophecy of tribal death. In the Devonian, the variety and number of the trilobites were greatly reduced (20 + 105), at a time when the ancient types of fishes, who undoubtedly fed on these crustaceans, began to be common in the seas. In the later Paleozoic seas, the trilobites were relics, or animals surviving from a time better suited to their needs, and one by one they vanished, until a little before the close of the Paleozoic era none were left. While they were in their prime, they dominated the life of the seas, since they were the chief carnivores and scavengers of Cambrian and Ordovician times, but with the rise of the fish-like animals in the Silurian and the true fishes in the Devonian their death knell was sounded by the incoming greater mentality and alertness of the vertebrates.

Habits. — Most trilobites could roll their bodies up like the sow-bugs or pill-bugs of our cellars, animals that are not insects but Crustacea (Isopods) and distant relatives of the trilobites. This rolling up was for the protection of the softer and more delicate parts of the ventral side, thus presenting to the enemy the hard, thick carapace, an effectual armor against other trilobites but ineffective against the fishes. The power of coiling up first appeared in the Upper Cambrian, and with the Ordovician all forms had adopted such a method of protection.

Size. — In size, the trilobites varied greatly at maturity, ranging in length from 0.38 of an inch up to 27.5 inches, but an average size was about 1.5 inches. Many species attained a length of from 3 to 4 and even 6 inches, but these were large individuals, and those above a foot in length were giants. Those represented as from 18 to 27.5 inches are, in nearly all cases, based on restorations pieced together from large fragments.

Large species appeared at different times and in every case seemed to occur near the zenith of the evolution of the stocks to which they belonged. With the sharp decline of the trilobites in the Devonian, no large forms are seen after Upper Devonian time.

The oldest giant forms lived in the Middle Cambrian, species of *Paradoxides* found in New Brunswick, Massachusetts, and Bohemia ranging from 12 to 14.5 inches (*P. regina*) and even to nearly 18 inches (*P. harlani*, Pl. 2, Fig. 1). In the Middle and Upper Ordovician there were many large trilobites; several were nearly 16 inches long (*Megalaspis gigas, M. heros, Asaphus barrandei*), and one form even reached a length of 21 inches (*Isotelus gigas*). The largest of all trilobites occurs in the Ordovician rocks of France and Portugal and is 27.5 inches in length (*Uralichas ribeiroi*). In the Silurian, there were many large forms but no giants. In the Lower Devonian, at least two giants, nearly 16 inches long, occurred (*Homalonotus major, H. armatus*), and in the Middle Devonian lived the last giant species (*Dalmanites*, 11 and 16 inches; *Calymene*, 8 inches; and *Terataspis*, from 18.5 to 24 inches). "With his extravagant armor of defense and aggression, *Terataspis grandis* must have been easy lord of his invertebrate domain and no very palatable morsel for the heavily plated fishes of his day" (Clarke).

Definition of Parts (study with Fig. 370). — The carapace of trilobites is divided transversely into (1) a head portion, called the *cephalon;* (2) a series of segments, forming the *thorax;* and (3) a tail-piece or *pygidium*, forming the abdomen. The *axis* is the area of the vital organs, while the *pleural regions* are protective coverings over the ventral limbs.

The cephalon is composed medially of the *glabella* and the outer *free cheeks* bearing the *compound eyes*. In many forms the free cheeks are separated from the glabella by a *facial suture* which generally shows as a faint raised line, and in all such forms the three parts are apt to separate after death and thus cause imperfect fossils. In some trilobites compound eyes are not known, such forms being called blind; usually, however, two more or less large compound eyes are present. In the majority of trilobites each compound eye is covered over by a single cornea and the individual lenses beneath may or may not show through. In others each lens has its own cornea. The number of lenses in a compound eye may vary from fourteen to the astonishing number of fifteen thousand. Imagine an animal with thirty thousand eyes!

The thorax consists of a variable number of articulating segments, the number being constant in the adults of each species, but variable in the young of each form and in the genera. There are never less than two, as in *Agnostus* (Pl. 2, Fig. 4), or more than twenty-nine. In a general way, it may be said that where there are many thoracic segments the pygidium is small, and where there are few the abdomen is large.

The pygidium or abdomen of trilobites may be small or large, and consists of a single piece of united segments varying between two and twenty-eight in number. Generally, the axial and pleural regions are plainly demarcated and some forms clearly show the number of coalesced segments.

Ventral Side. — Beneath the glabella and hinged to its bent-over and thickened posterior margin is the *hypostoma* or upper lip cov-

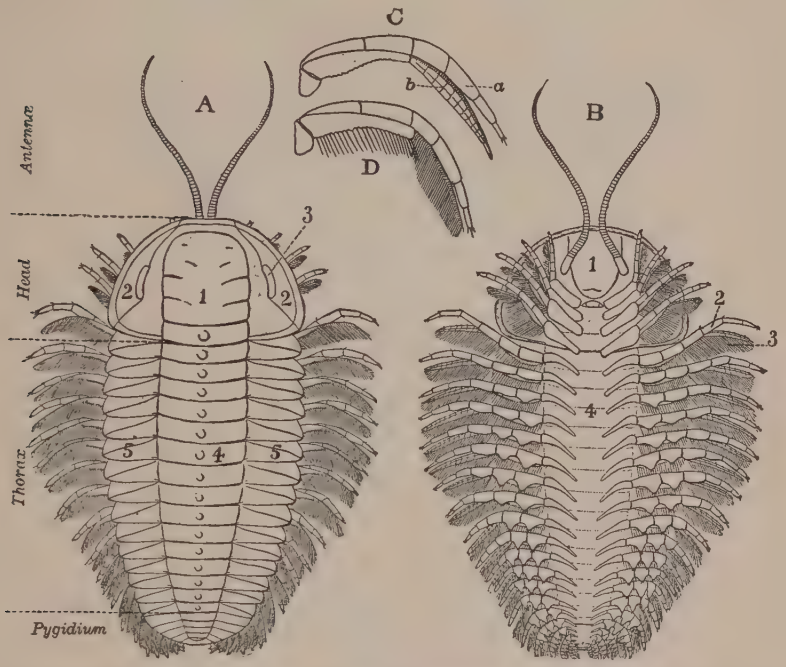


Fig. 370. — Sketches of a complete trilobite (*Triarthrus becki*). × 2. After Beecher. *A*, dorsal or upper side of carapace, showing three lobes, pleura (5), rachis or axis (4), glabella (1), and free cheeks (2) which bear the eyes (3). *B*, ventral or under side, showing biramous limbs (2, 3) attached to rachis, and upper lip or hypostoma (1) which covers mouth. *C*, one of the double legs stripped of setæ or breathing organs. *D*, another leg with setæ attached; the upper member of the leg is for breathing and swimming and the lower part for crawling.

ering the mouth (Fig. 370 *B*). On each side of this plate there may be a pair of short or long antennæ, or many-jointed sensory or feeling organs. Otherwise, all the limbs are in pairs, and each limb is double, or biramous, with each of the two branches, in turn, made up of many joints.

The head has four pairs of such biramous limbs which serve also for chewing the food and passing it into the mouth. Back of the head each thoracic and abdominal segment has its similar pair of biramous limbs. Both limb

branches arise from a single basal joint fastened to the axis; one stouter ramus or leg branch with fewer joints serves for crawling, while the other, which is more delicate and much more jointed, serves for swimming and is also replete with long hair-like appendages that are delicate tubes in which the circulating blood extracts from the water the necessary oxygen for life sustenance (Fig. 370 *D*).

Trilobite Moulting. — As trilobites grow, they periodically shed their chitinous shell, as do the crabs, and this happens many times before they attain full growth and probably occasionally during maturity. During the time of moulting the animals grow and the detailed characteristics are changed, along with the introduction of new segments. At first, the trilobite is a very minute, apparently unsegmented animal, all head (Pl. 6, Figs. 14, 15); then it consists of head and pygidium, the latter of which rapidly adds more segments; these stages are followed by other moults that long before maturity is attained rapidly introduce the full number of thoracic and pygidial segments according to the characteristics of each species. Later moultings simply enlarge the individuals.

Evolution. — Trilobites are the most primitive of Crustacea and appear to have arisen out of crawling worms, or, more probably, annelids, in Proterozoic time. In the Lower Cambrian many of the trilobites were primitive and betray their annelidian ancestors in their abundant and variably segmented thorax and very small tail. In pre-Cambrian time the annelidian stock from which came the trilobites also gave rise to the sea-scorpions or eurypterids (Pl. 12), and, along a third line of evolving forms, to the horseshoe crabs or limulids. Out of the eurypterids in the Middle Silurian came the scorpions and through these the entire class of arachnidian (spider-like) animals, such as scorpions, spiders, and mites. It is thought that out of some Silurian or Devonian trilobite that habituated itself to the land-waters and became amphibious was derived the stem stock of insects. The Crustacea have probably also developed out of trilobites which gave rise to the stock Phyllopoda in pre-Cambrian times, these latter in turn giving rise to the degenerate Ostracoda or bivalved Crustacea in the late Cambrian and to the Cirripedia or barnacles in the Ordovician. Another line of Crustacea arose in the Phyllocarida in the Lower Cambrian or earlier, and out of these probably came all of the remaining Malacostraca.

CHAPTER XXXIII

SHELLED ANIMALS

Shelled animals constitute the bulk of the fossils that the student of extinct invertebrates meets with in the sedimentary rocks. They are exceedingly varied, but in this book only those stocks will be studied that have especial significance in Historical Geology. The older naturalists also included among the Mollusca — the true shell-fish such as clams, oysters, conchs, etc. — the class Brachiopoda, and they are here considered with them, but this is done only for convenience of presentation, and it should be clearly understood that the relationship between the Brachiopoda and the Mollusca is remote, both stocks having independent origins and very different ancestors, as will be seen in the further consideration of them. The mere fact that brachiopods have two valves somewhat similar to the two shells of bivalves such as oysters, mussels, etc., has no further significance than that in both stocks they are protective coverings for the soft bodies of the animals within.

There are other animals with external shells besides the Mollusca and Brachiopoda, and the terms lobster shells, crab shells, etc., are in popular usage. The coverings in these latter cases are composed largely of nitrogenous substances (chitin), yet they also have much carbonate of lime or phosphate of lime. While these animals are shelled, the biologist does not include them among the true shell-fish, and they are not considered in this chapter.

Brachiopods or Lamp Shells

(See Pls. 1, 2, 4, 9, 17, 22)

Geologic Occurrence. — Brachiopods are common fossils throughout the world in most of the marine formations of the Paleozoic and Mesozoic eras and are therefore of especial importance as index fossils in Stratigraphy and Historical Geology. They are present in the very oldest beds of the Lower Cambrian, but in few forms, though at times abundant in numbers. However, long before the end of this period at least three of the four orders into which the class is divided were in existence. This means that brachiopods origi-

nated in the later part of the Proterozoic era. There are about 160 living forms and fully 7000 fossil species. Brachiopods were in greatest profusion in the Paleozoic, there being in North America alone more than 2100 kinds restricted to this era. Throughout the Mesozoic, however, our continent was poor in brachiopods, less than 75 species being recorded, while in Europe the seas swarmed with them. In the Cenozoic they no longer are a conspicuous class of fossils, their number being greatly reduced, and probably at no time in this era were there more species than are living today. In North America less than 20 Cenozoic forms have been recovered. It was in the Ordovician that the brachiopods began to bloom out into varied forms and the class had its evolutional culmination in the Devonian, where 30 per cent of the American Paleozoic species occur. There was then more or less of a decline throughout the Carboniferous and a marked vanishing of stocks during the Permian period. In the late Triassic a new evolution set in, especially marked in the succeeding Jurassic in certain brachiopod stocks known as the rhynchonellids and terebratulids, whose descendants are most abundant in the present seas. The genera *Lingula* and *Crania* are believed to be the longest-lived kinds of animal stocks known, having persisted through all the physical changes since the Cambrian.

Habitat. — All brachiopods are sexed, gregarious, marine animals, living from the strand-line down into the great oceanic abyss of more than 3 miles in depth. Their greatest abundance, however, is in the shallow water down to 1000 feet, where fully 80 per cent of the living forms occur, while 70 per cent live above 600 feet of depth.

Arm Structure. — The word Brachiopoda means *arm-footed* and was given to the group because of a false physiological interpretation of the brachia or arms, for the animals do not crawl on their arms as was thought in 1806 when the word was coined (see Figs. 371, 372). The two more or less looped or spirally rolled, fleshy, fringed arms, on the contrary, serve two functions: first, through movements of the cirri and their cilia (the fringe) they attract currents of water into the shell, where the microscopic food, chiefly algæ, is extracted from it and fed into the mouth; second, they serve for respiratory purposes, that is, for the absorption of the oxygen so necessary for sustaining the vital force.

In many brachiopods the arms are unsupported by internal calcareous skeletons, but in the majority there are such supports and they are of much value in the zoölogical classification of these

lowly animals (see Figs. 371, 372). The most primitive supports consist of two short, sickle-shaped hooks known as *crura*. When these are more or less long and united in the middle, they are called

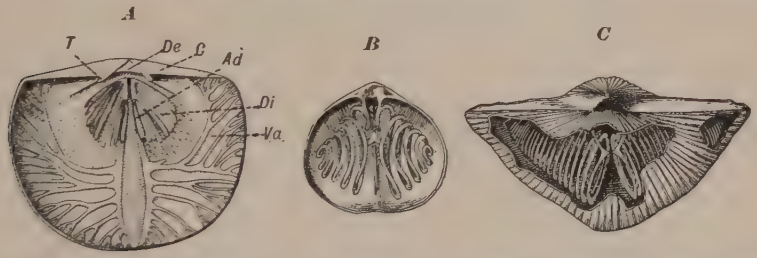


Fig. 371. — Internal characters of brachiopods. *A*, ventral valve of a strophomenid (*Rafinesquina expansa*). *B*, dorsal valve of a spire-bearer (*Nucleospira*), showing the skeleton that supports the arms. *C*, both valves with the dorsal shell broken to show the spiralia (*Spirifer striatus*). After Davidson. *Ad*, adductor scars; *C*, cardinal area, which also makes the hinge of the valves, and to which are attached the teeth (*T*); *De*, open delthyrium where the pedicle emerged; *Di*, diductor muscle scars; *Va*, vascular markings.

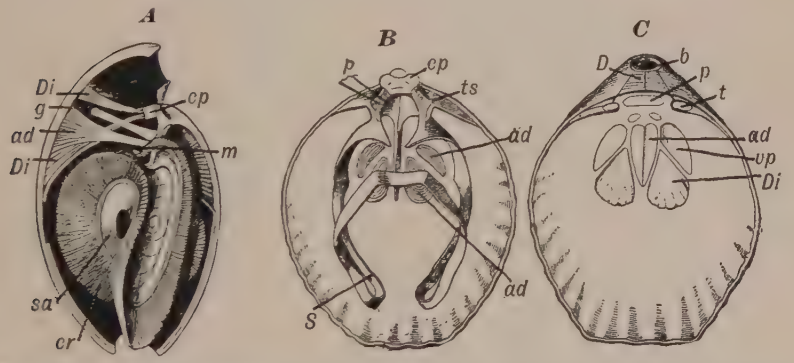


Fig. 372. — Internal structures of a loop-bearing brachiopod (*Magellania flavescens*). After Davidson, from Zittel's *Handbuch*. *A*, the shell and animal in section from the side. *B*, dorsal interior with loop or skeleton that supports the arms. *C*, ventral interior, showing muscle scars. *ad*, adductor muscles, two in ventral and four in dorsal valve; *b*, foramen through which pedicle emerges; *cp*, cardinal process to which are attached the ventral diductor muscles (*Di*); *cr*, cirri on edges of arms; *D*, two deltidial plates closing delthyrium; *Di*, diductor muscles that cross over to the cardinal process (*cp*); *g*, gut ending blindly; *m*, mouth area; *p*, place where pedicle is attached to shell; *S*, calcareous loop; *sa*, fleshy arms covering loop; *t*, teeth; *ts*, grooves into which articulate teeth of ventral valve; *up*, ventral pedicle muscles.

loops (Fig. 372 *B*), shells of this type being common after the Paleozoic; but when they bend outward into spiral coils, they are referred to as *spirals*, a type seen chiefly in the Paleozoic (Fig. 371 *B* and *C*).

External Structure. — Brachiopods have two valves (shells) which are situated on the ventral (belly) and dorsal (back) sides of the animals, and are hence known as the dorsal and the ventral valves (Fig. 373). In bivalved molluscs, on the contrary, the shells are on the right and left sides of the animal, and are therefore called the right and the left valves. In addition, the soft parts of these two types of invertebrates are markedly different. Issuing from the ventral valve in the brachiopods there is a short, or in some types a very long, worm-like body known as the peduncle or pedicle (Fig. 373 *A*), a fleshy stem, which in the great majority of cases anchors the animal to some foreign object on the sea bottom, and the individuals stay throughout life fixed to one

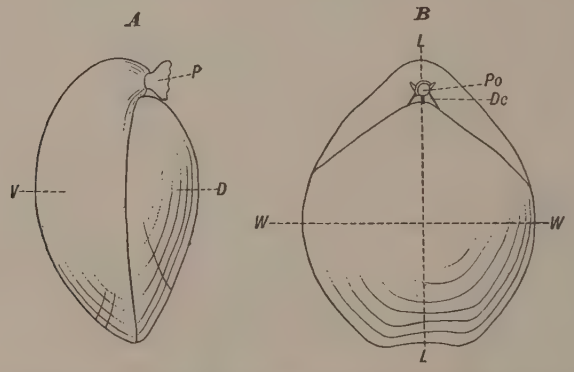


Fig. 373. — Diagrams of a lamp shell or brachiopod from the side (*A*) and dorsal view (*B*). *D*, dorsal valve; *Dc*, delthyrium, closed by two deltidial plates; *L*, length of shell; *P*, short pedicle by which the animal is permanently attached to foreign objects; *Po*, pedicle opening or foramen; *V*, ventral valve; *W*, width of shell.

place, the new-born young alone being free, and remaining unattached for some days or, rarely, two to three weeks. It is only exceptionally that brachiopods in later life are without a peduncle and then the ventral valve is more or less cemented to some hard object, or otherwise held in place.

The shells of brachiopods are either phosphatic (phosphate of lime) or wholly calcareous (carbonate of lime). When phosphatic, they are usually thin and do not have ventral *teeth* and dorsal *dental sockets* or *hinge-lines* for the hinging or articulation of the valves (Figs. 371 *A*, 372 *B* and *C*); such forms are said to be inarticulate, this structure being used in dividing the brachiopods into two subclasses, the *Inarticulata* and the *Articulata*. All of the calcareous-shelled brachiopods are more or less well hinged

and therefore articulate. The shell substance is said to be *impunctate* when there are no minute perforations passing through, and *punctate* when there are closely set canals in the valves. These cannot be seen with the naked eye, but with a pocket lens any punctate brachiopod is readily made out.

Internal Characters. — The shells are secreted by the *mantle*, which consists of two thin membranes that are not united marginally and have the form of the inside of the valves. They completely cover the soft parts of the animal, like skins, and their inner surfaces are respiratory, as are also the brachia (arms) within the front mantle cavity.

On the inside of the two valves are usually seen *muscular impressions*, or markings on the places where the muscles were attached. These scars are different in the dorsal and ventral shells, and more or less variable throughout this class of animals. Only the most important and largest of them need, however, be mentioned. In the ventral valve in the middle line are two small elongate scars called the *adductor impressions* (Fig. 372 *A* and *C*). These represent the places of attachment for the adductor muscles, or those which by contraction close the shell. The adductors pass over to the dorsal side, where they divide and are attached in four places, making the only prominent scars of the dorsal valve (Fig. 372 *B*). On each side of the adductor impressions in the ventral valve are two large *diductor scars* (Figs. 371 *A*, 372 *C*), left by the diductor muscles, which open the shell and which pass backward to the posterior region of the dorsal valve and are there attached to a protuberance known as the *cardinal process* (Fig. 372 *A* and *B*).

Mollusca or Shell-fish

Nature of Mollusca. — The Mollusca present a greatly diversified array of bilaterally symmetrical animals popularly known as shell-fish, of which it is estimated that fully 45,000 kinds are now living. Such are the clams, oysters, snails, and the pearly nautilus. They are soft-bodied animals, often inhabiting shells to protect themselves against their enemies, though there are many without the protective shells. The general term by which naturalists speak of them is Mollusca, meaning soft. As a rule, they are very sluggish and have unsegmented bodies. Though they are devoid of limbs for crawling or swimming, most of them do, however, move about, accomplishing this by means of the so-called *foot*, a creeping sole situated underneath the belly. Usually the

body is covered by a *mantle*, a thin membrane that secretes the shell when such is present. Within the *mantle cavity* lie the *gills*, organs of varied construction setting up currents of water, out of which is extracted not only the oxygen for respiration but often also the food for life sustenance. In the land snails there are no gills and here the mantle cavity has been adapted into a kind of lung for aërial respiration, since they breathe the air. In all of the molluscs, except the bivalves, the mouth is furnished with a flexible chitinous ribbon known as the *radula*, a sort of tongue, usually provided with numerous minute, sharp, hard teeth and moved by special muscles for the breaking up of the food. The sexes are separate, or united, the individuals in the latter case being hermaphrodites.

Habitat. — The chief habitat of the Mollusca is the shallower parts of the seas and oceans, but some live in the fresh waters of the land, and the snails even live abundantly on the land at all altitudes where there is vegetation.

Nature of the Shell. — The shells usually consist of three layers: an outer, very thin, brown, horny layer always absent in the fossils; a thick, middle, limy layer referred to as the porcelanous layer, the one most often preserved in the rocks; and an inner, generally thick, mother-of-pearl, prismatic layer that is often destroyed in the fossils, especially among the Paleozoic molluscs, since it consists of an easily dissolvable form of carbonate of lime known as aragonite.

For the purposes of Historical Geology only three classes of molluscs need be studied, namely, Lamellibranchia, Gastropoda, and Cephalopoda.

Lamellibranchia

The name Lamellibranchia comes from *lamella*, meaning *leaf*, and *branchia*, meaning *gills*, and was chosen because in these molluscs the gills are leaf-like. The class is also widely known as *Pelecypoda*, meaning *hatchet-foot*, because the foot often has the shape of a hatchet (Figs. 374 *A* and 375 *A*). The group includes all the headless and therefore *degenerate Mollusca*. The body is usually compressed from side to side and always covered with two shells or valves, one on the right, the other on the left side (Fig. 374 *A* and *B*). They are therefore often called *bivalves*, and are popularly known as mussels, clams, oysters, cockles, and scallops. Their habitat is mostly marine, in the shallow waters near the shores, where their food, the microscopic algæ, is most abundant.

Nearly all fresh waters, however, have some mussels, but none have been adapted to live out of the water on the land. The food is strained out of the water by the gills (actually the labial palps), which are also the breathing organs. The lamellibranchs are very sluggish animals, many remaining buried in the sand and muds of

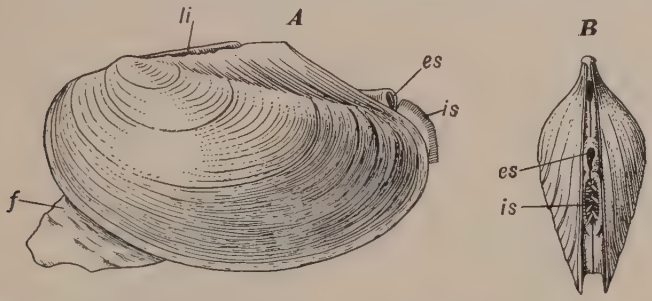


Fig. 374. — A fresh-water pearl shell (*Anodonta*). *A*, animal as seen from the left side. *B*, from the posterior end. After Howes. *es*, exhalant siphon; *f*, digging and crawling foot; *is*, inhalant siphon; *li*, ligament that opens valves.

the sea (Fig. 375 *A*). The scallops only can swim a little by clapping their valves and forcing water alternately from one side and then the other.

Shell Characters. — The two shells lie on the right and left sides respectively and are joined on the dorsal side of the body by a *hinge*, a more or less thickened area provided with teeth and sockets, allowing the valves to move upon one another (Fig. 375 *B* and *C*). Either on the outside or within the thickened shell mass of the hinge area there is an *elastic ligament* attached to both valves that acts like a spring and keeps the shells open when the animals are in repose (Fig. 374 *A*). On the inside of the valves are muscle scars, usually one at each end of the shell, these being due to the *anterior* and *posterior adductor muscles*, though in many forms, as in the oysters, there is only one of these scars situated near the center of the valve (Fig. 375 *B* and *C*). These muscles close the shell, and when it is shut the elastic ligament is under strain ready to open the valves again as soon as the adductors let go their pull. The wedge-shaped *foot* of the lamellibranchs is large in the creeping forms but more or less reduced in size through disuse, according to whether the animals live in holes, like the soft clam, or have one shell firmly cemented to some hard object on the sea bottom, as in the oysters.

Siphons. — In most lamellibranchs the mantle elongates beyond the shell into two tubes or siphons through which the water of res-

piration enters and leaves the mantle cavity (Figs. 374 *A*, 375 *A*). When the siphons are large, it is an adaptation for living buried in the sand or mud, and all lamellibranchs with such siphons have the shells marked on the inside by a decidedly bent line, the *pallial sinus*, seen in connection with the posterior adductor muscle.

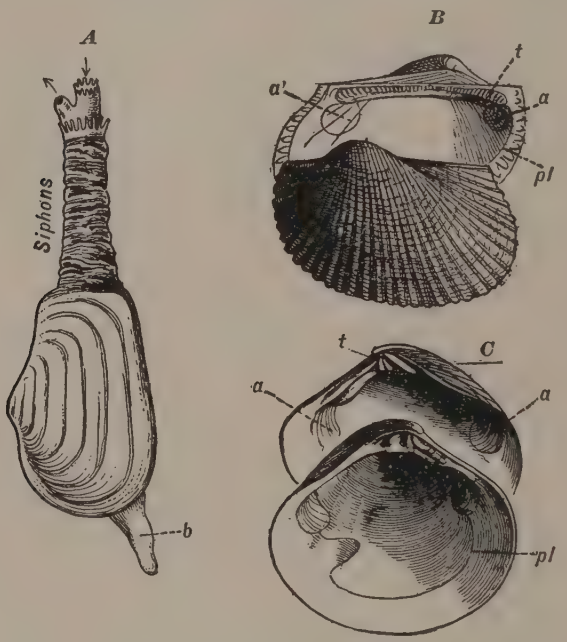


Fig. 375. — Bivalves. *A*, marine bivalve (*Mya*) that lives buried in the mud. The long, partially retractile tube is the outer covering of the siphon. After B. B. Woodward. *B*, the two valves of *Arca* from the outside and inside. *C*, another type of bivalve (*Meretrix*). After Zittel's *Handbuch*. *a*, adductor or closing muscles; *pl*, pallial line where mantle is attached to shell; *t*, teeth of shell articulation.

Geologic Range. — Lamellibranchs were exceedingly rare in the Cambrian and were not well established until the Ordovician, after which time they became more and more abundant and are very prolific in all the shallow waters of the present oceans. While the shells of these bivalves are often abundant in the Paleozoic rocks, they are usually not well preserved until the Pennsylvanian, a condition seemingly connected with a rather thin porcelanous layer and a comparatively thick mother-of-pearl one, the latter being easily destroyed. They are only occasionally of value as stratigraphic markers in the Paleozoic, but, beginning with the Meso-

zoic, they are abundantly preserved and often serve as index fossils. Oysters appeared in the Mesozoic but were small and comparatively insignificant in species or individuals until the later Jurassic, since which time they have served as food for many diverse stocks of invertebrate and vertebrate animals.

Gastropoda

General Characters. — The name Gastropoda means *stomach-footed*, and has reference to the fact that the animals creep about by contractions of the sole of the foot, which lies on the ventral side (Fig. 376 *B* and *C*). This class of molluscs, which are as a rule sluggish, though less so than the lamellibranchs, is exceedingly varied and embraces not only such shelled forms as the limpets, drills, periwinkles, whelks, conchs, and snails, but also the naked sea slugs and the slugs of the land. They are most abundant and varied in the shallow seas, where they crawl over the bottom, are far less varied in fresh water, and on the land are represented by the vegetarian, air-breathing or pulmonate snails (so-called because the mantle cavity acts as a lung in respiration, see Fig. 376 *C*), which are found in nearly all places where plants grow, and are very varied the world over. The mantle cavity in the aquatic forms usually has but a single gill, the one on the right side, that on the left side having been lost because of the spiral form of the body. In habit they are, as a rule, herbivorous, less often carnivorous and scavengers. The mouth is provided with a radula or tongue-like process. The carnivorous forms known as drills

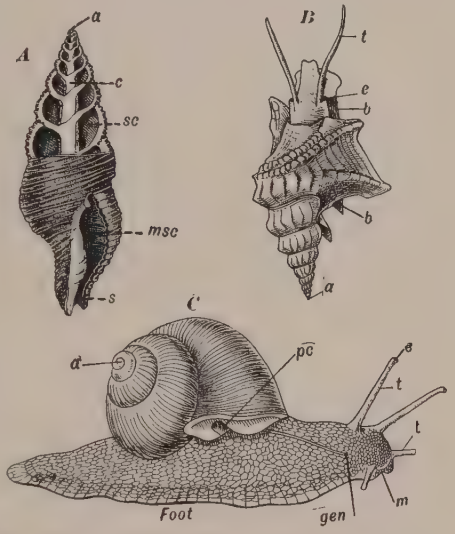


Fig. 376. — Gastropods. *A*, regular marine gastropod (*Latirus*), with the spiral shell wound to the right (dextral). After Steinmann. *B*, another marine gastropod (*Aporrhais*), with the animal crawling. After B. B. Woodward. *C*, an air-breathing (pulmonate) land snail in the act of crawling, the head with pairs of sensory tentacles, the long ones bearing eyes. After Hatschek and Cori. *a*, apex of shell; *b*, foot; *c*, interior columella; *e*, eye; *gen*, genital opening; *m*, mouth; *msc*, mouth of shell cavity; *pc*, opening into pulmonary cavity; *s*, siphonal cavity; *sc*, interior shell cavity; *t*, sensory tentacles.

bore holes into their shelled victims, such as the clams, with the radula and the aid of a weak secretion of sulphuric acid. The head of most gastropods is usually distinctly marked off from the rest of the body, and has a pair of eyes and one or two pairs of sensory organs or tentacles (Fig. 376 *B* and *C*).

Spiral Shell. — The usual form of the shell or protective covering is a spirally twisted, right-handed (dextral) cone with the apex directed upward (Fig. 377 *C*); it is secreted by the mantle situated on the dorsal side of the animal. Because of this single shell, the gastropods are also spoken of as *univalve molluscs*. In many forms, however, there is a chitinous or calcareous *operculum*, a plate attached to the side of the foot, which closes the shell opening when the animal has retreated into its shell or is retracted. Even though gastropods may thus have two shells, these together do not represent the two valves of bivalves. It is only the spiral

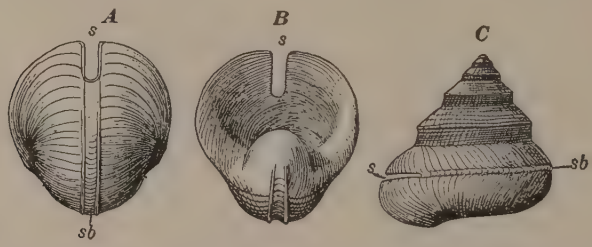


Fig. 377. — Two species of primitive marine gastropods. *A*, *B*, a form wound in a plane (*Bellerophon*). *C*, a form with a depressed spire (*Pleurotomaria*). After Zittel's *Handbuch*. *s*, slit or opening for siphons; *sb*, slit-band, the progressive track of the slit.

cone that corresponds to the valves, because the operculum is a secondary structure not present in all univalves, is secreted by the foot, and has nothing to do with the dorsal mantle or true shell secretion.

Geologic Range. — Primitive forms of Gastropoda were present in the Lower Cambrian, where practically all of them were more or less conical, not twisted, but resembling little hoods. The twisted type of cone appears more and more abundantly in the Upper Cambrian and since the Ordovician has been common as fossils. At present there are living more than 20,000 species, a larger representation than at any time during the geologic past. In the Paleozoic they are, as a rule, defective fossils and it is only since the Mesozoic that their abundance in well preserved specimens is of value in Historical Geology. The air-breathing gastro-

pods appear rarely in the Pennsylvanian and seem not to have been common until late in the Jurassic, where are also seen the first fresh-water snails. There are about 500 species of fossil pulmonate snails known and about 6000 kinds of land snails.

The *Pteropoda*, or sea butterflies, are in general a group of small, active, pelagic gastropods, highly modified and with very thin transparent phosphatic shells (Fig. 378). They spend their lives in the upper part of the oceanic waters. The foot is modified and flattened out into two lateral folds or wing-like structures (hence they are also called winged snails) by means of which the animal swims. The pteropods are often found fossil in the Devonian and subsequent rocks. Those of the early Paleozoic, however, were heavy-shelled forms with totally different habits, crawling on the bottom of the sea; these were the *Hyolithes* and *Tentaculites* which were common in Cambrian to Silurian time. In the Middle Ordovician there was also a great abundance of minute pelagic gastropods known as *Cyclora*, which had very thin phosphatic tests. Their interest in this connection is that in Tennessee they are so common in the Ordovician limestone that when these rocks are decomposed into a residual red clay, the Cycloras remain undissolved and concentrated as a phosphate of lime, which is much sought after for fertilizing purposes.

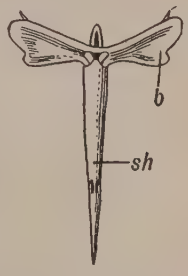


Fig. 378. — A sea-butterfly or pteropod (*Styliola*). Much enlarged. After Adams, from Zittel's *Handbuch*. *b*, foot or fin, the swimming organ; *sh*, shell.

Cephalopoda

Cephalopoda (means *head-footed*) are the most highly organized Mollusca and include such animals as the nautilus, ammonites, octopus, cuttlefish, and squid. All are exclusively marine. The two former types of cephalopods have chambered shells in which the animals live, while the latter stocks are devoid of these, though in the cuttlefish and squid there is more or less of an internal skeleton often preserved as fossils. In the Mesozoic there lived abundantly another stock known as the belemnids, with thick cigar-shaped internal skeletons that occur abundantly among fossils. For present purposes the nautilids only will be described, because they are decidedly characteristic of the Paleozoic, and the remainder will be considered when Mesozoic animals are studied, for their chief development lies in that era (Chapter XLVIII).

Pearly Nautilus (see Fig. 379). — The nautilids are the oldest and most primitive division of the class Cephalopoda. They were sparingly present in the Upper Cambrian, and had an abundant Paleozoic representation beginning with the Ordovician. The word nautilus is a poetic form of the Greek word for sailor, and like their distant relatives, the argonauts, it was believed that these animals could

expand certain of their arms into the wind and so sail the seas. This idea, however, is wrong, for the four living species of the genus *Nautilus* now inhabiting Oceanica from the Malay region to the Philippine and Fiji islands have never been seen at the surface except in a dying condition, though their empty sealed

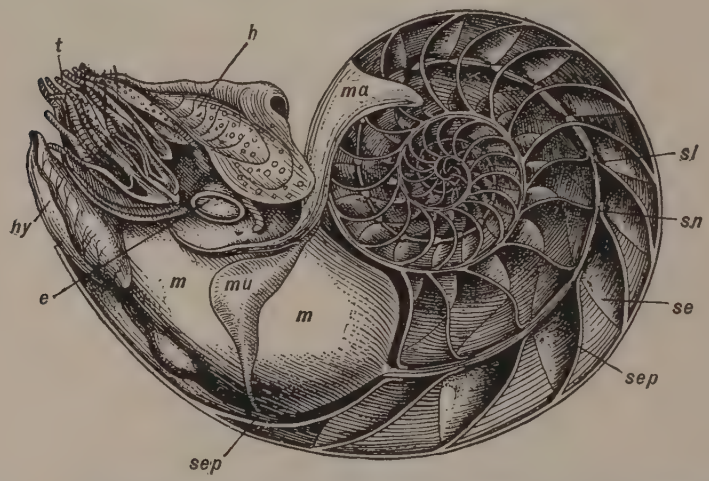


Fig. 379. — Pearly nautilus, with the shell cut through center to show internal chambers; the animal is fully expanded to show all of the external characters. $\times \frac{1}{2}$, After Hancock. *e*, large eye; *h*, hood or protective covering for the animal when retracted into the shell; *hy*, hyponome or funnel where water leaves mantle cavity; *m*, mantle, which encases animal and secretes shell (note prolongation into siphuncle); *ma*, dorsal prolongation of mantle; *mu*, muscle attaching animal to shell; *se*, chambers; *sep*, shell partitions or septa; *si*, siphon and siphuncle extending from animal through all the chambers to apex of shell; *t*, tentacles around mouth.

shells drift to Japan, Africa, and New South Wales. The nautilids are gregarious animals of the deeper and warmer sea between 300 and 600 feet, at a temperature of 68° F., but they have been taken in 1000 feet of water. In habit they are fierce and decidedly carnivorous and will take the meat that baits the fish-pots at depths down to 420 feet.

The popular name, *pearly nautilus*, is derived from the fact that these beautiful, bilaterally symmetrical shells are often used as ornaments and for pearl buttons, after the thin, outer, porcelanous, striped layer has been removed from the much thicker, inner, mother-of-pearl one. They are also known as *chambered shells*, because the cone, of whatever form it may be, is regularly chambered by thin, pearly, transverse partitions called *septa*, which

the animal secretes at regular intervals along the posterior side of its body after it has moved a short distance forward in the living chamber. These septa are concave toward the opening of the shell, and are perforated by a circular hole which terminates behind in a funnel. Through this funnel and the perforations there passes a fleshy tube known as the *siphon* (Fig. 379, *si*), originating on the rounded posterior side of the animal and continuing through all the chambers to the final minute one at the apex of the cone, where it is fastened to the inner side of the wall. In many fossil forms the siphon has secreted a calcareous tube, either straight or bent, known as the *siphuncle*, which at times is very thick; whatever may be its nature, it is thought to have been porous, permitting the animal to send through it into the chambers a gas to make the shell more or less buoyant, and thus to render the weight of its stony house but little of an encumbrance in its movements. The nautilids crawl over the bottom of the sea, or hold to it by their ninety retractile tentacles, and can swim rapidly backward in a jerky manner by forcing out water through the *hyponome* or *ambulatory funnel*, which consists of two flaps, the thickened ends of the mantle that envelops the animal and meets in the middle of the ventral side (Fig. 379, *hy*). To the sides of the cone the septa are firmly united, but in the fossils it commonly happens that the outer shell is lost, in which case the edges of the partitions show plainly as so many lines in the rock-filled cone. As the nature of these lines is of much importance in classifying shell-bearing cephalopods they are termed *suture lines*. Usually these suture lines are straight, but there are forms in which they are decidedly bent in lobes. These, when convex toward the apex of the cone or backwardly directed, are termed *lobes*, and when curved toward the larger end or aperture of the shell, are called *saddles*.

Nature of the Fossil Forms. — Nautilids appeared in fair abundance in the Lower Ordovician. Among these the most primitive were straight, tapering cones that were circular or oval in outline, and because there are many families of them they are called *Orthoceracones* (from the genus *Orthoceras*, meaning *straight horn*, Pl. 5, Fig. 17). These orthocerids were common throughout the Paleozoic and particularly so in the Ordovician and Silurian, when individuals are known that originally had a shell as long as 15 feet (*Endoceras*). With the Devonian these primitive forms began to wane slowly, but some were still present in the Triassic. All other types of cephalopods had their origin in the straight-shelled Orthoceracones and the first of these had their cones slightly

bent and are therefore called *Cyrtoceracones* (from *Cyrtoceras*, meaning *bent horn*, Pl. 5, Fig. 18); later descendants were coiled in a loose spiral wound in a plane and are known as *Gyroceracones* (from *Gyroceras*, meaning *round horn*); still others are tightly wound, with the whorls embracing one another more or less closely, as in *Nautilus*, and these are termed *Nautilicones*. On the sides of such one sees more or less of the inner whorls of the shells, and the area of these whorls is spoken of as the *umbilicus*. It is small in *Nautilus* and wide or open in the Ordovician forms. The bending of the tubes is due to a more rapid secretion of lime along the ventral side of the cone, and the greater the unequal growth the more rapidly the cone involutes or rolls up. Nautilids persisted into the Mesozoic and were most abundant in the earlier half, after which time they gradually disappeared and are seen to-day only in the four relic forms, which give us our sole knowledge of the soft parts of the many thousands of kinds that swarmed the ancient seas.

Cephalopods are divided into two subclasses, the Tetrabranchiata and Dibranchiata, on the basis of the number of plume-like gills used to oxygenate the circulatory blood. In the former subclass there are four gills (*tetra*, four), and the latter division has but two. The Tetrabranchiata, all of which have external shells, appeared in the Cambrian, and have now almost vanished from the earth, while the Dibranchiata, which are in almost all cases naked but may have internal vestiges of the ancestral outer shell, arose in the Triassic and are abundantly represented among living cephalopods by the squids, argonauts, and octopus.

Below the visceral sac is situated the large *mantle cavity* with its gill-plumes, where water is freely taken in and passed out through the funnel. When the animal wishes to swim, however, the two flaps of the mantle are appressed, forming the funnel, and by a rapid contraction of the mantle or gill chamber the inhaled water is shot out with great force. The animal then darts backward or sidewise according to the direction in which the stream is ejected. They are expert and rapid swimmers, according to Wiley. The eyes on either side of the head are large, of primitive structure, and supported on short stalks called peduncles. The mouth is surrounded by the tentacles and is provided with two powerful, protrusible, horny, parrot-like bills, the upper one of which among fossil forms was often tipped with a carbonate of lime beak.

CHAPTER XXXIV

ORDOVICIAN TIME AND THE REIGN OF INVERTEBRATE ANIMALS

General Characteristics. — The Ordovician system of rocks lies above the Cambrian and beneath the Silurian systems. It represents the closing period of the Early Paleozoic sub-era, during which the marine invertebrate animals were the highest expression of life. Fully 1000 species are known from the Cambrian, whereas the Ordovician has at least five times as many described forms. The period was, therefore, one of marvelously great evolutional progress. As the land flora of this time seems to have been too soft and perishable for preservation in the sediments, practically nothing of it has been recovered, while the fragments of fishes abundantly preserved in Colorado, South Dakota, and Wyoming, but nowhere else, are negligible. We may therefore characterize the Ordovician as the time of marine invertebrate dominance, since all the grander divisions and subdivisions of this type of animals were then represented (see Pls. 4–6).

History of the Term Ordovician.—It was Professor Lapworth of Birmingham University in England who in 1879 proposed the term *Ordovician* (after an ancient tribe, the Ordovices, who at the time of the Roman Empire lived in Wales) to replace the Lower Silurian of Murchison (1835).

Fig. 380. — Adam Sedgwick, at the age of forty-seven. Author of Cambrian and Devonian systems.

Sedgwick first studied these beds in Wales (1831) and he contended for many years that they should be called Cambrian, but this latter name has been restricted to his Lower Cambrian, in which he found no fossils. In many parts of Europe Lower Silurian is still used for this, the second period of the Paleozoic, but it certainly is not conducive to clear thinking to refer to two systems by the

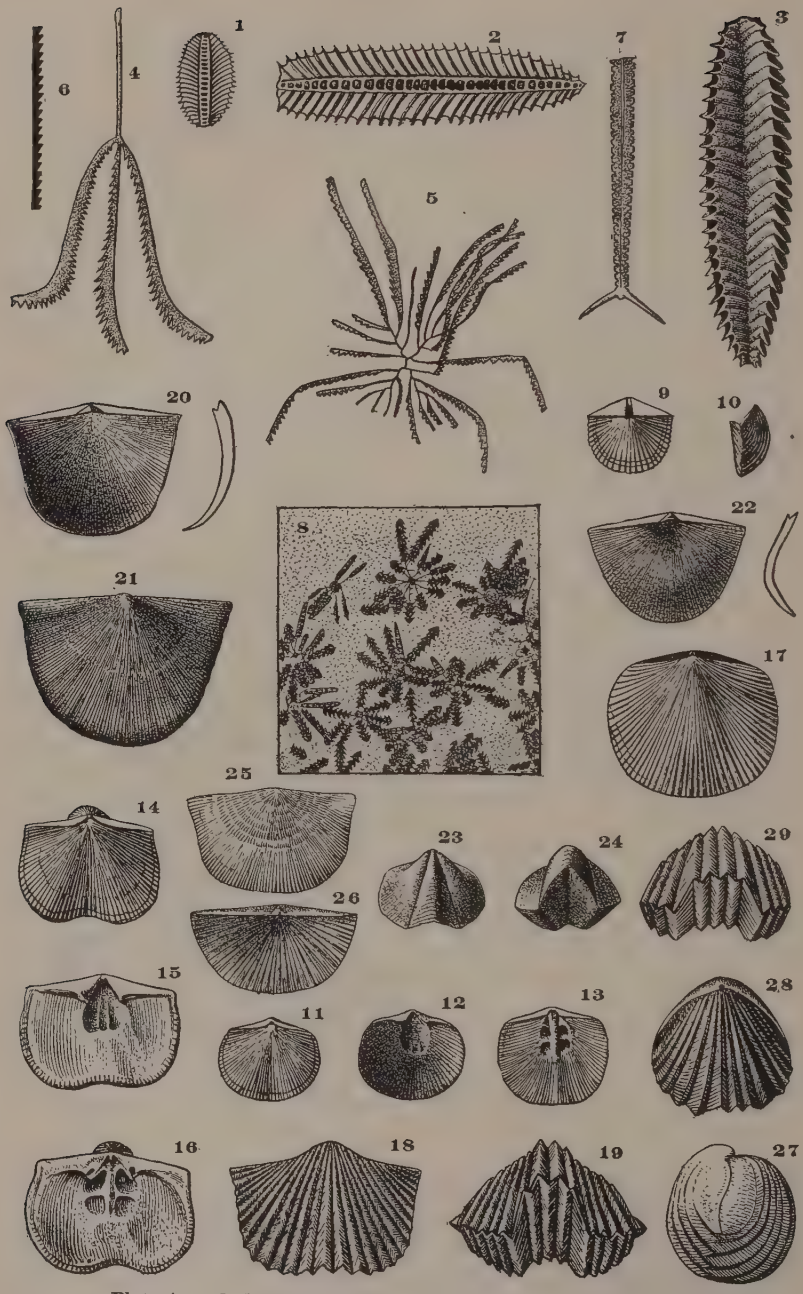


Plate 4. — Ordovician graptolites (1–8), and brachiopods (9–29).

See Appendix B.

one name of Silurian and to speak of them individually as Lower Silurian and Upper Silurian, thus giving the impression that the two systems are but parts of one — the Silurian. In the type area of the Silurian in England, each division has its independent faunal characters, and, furthermore, they are separated by an unconformity. Consequently, for the sake of fixity in nomenclature, geologists are gradually accepting, though under protest, Lapworth's substitution of Ordovician for Lower Silurian. But if Ordovician, as now widely used, can be shown to embrace two or even three systems, the time will have arrived for a redefinition of both Cambrian and Ordovician.

Ordovician System of Rocks

Acadian Area. — Throughout most of North America the beds of Ordovician time are in the main of limestones, with some calcareous shale, and the period may well be spoken of as one essentially of limestone making. However, throughout the New England States, other than Vermont, and the Maritime Provinces of eastern Canada south of the St. Lawrence River, wherever Ordovician strata are known, they are dark to black shales and greenish sandstones with but little limestone, ranging in thickness from a few hundred up to more than 2000 feet. This region is an independent marine province and belongs to the Atlantic realm, much of its life being more like that of western Europe than of the closely adjacent Central Interior sea. The region was more or less in connection with the Central Interior sea, but only at one time did it markedly feel the latter's influence, and this was toward the close of the Middle Ordovician, when the late Trenton sea was invaded by the Atlantic fauna and its dark, muddy waters.

Logan's Line. — As one steams down the majestic St. Lawrence from Montreal to Quebec, there are seen on the left or north side of the river the little disturbed and nearly horizontal Middle Ordovician strata resting against the Laurentian Hills, which are first discerned in the distance and come nearer as one approaches Quebec. On the south side of the river, however, all the way to the land's end at Gaspé, the Ordovician strata are in confusion — a folded, crumpled mass of great thickness, known to Canadian geologists as the Quebec series, and naturally presenting many difficult problems of stratigraphy. To the north of the river are the remnants of the Early Paleozoic sediments deposited by the Central Interior sea, while to the south is the Acadian mass of sediments of the same and later time, laid down by still another sea having Atlantic connections. This latter material has been thrust, no one as yet knows how far, upon the strata of the other sea province. The river therefore runs along a fault line, first determined by Logan, and hides the contact between the two series all the way from Anticosti to near Montreal; then the fault leaves the course of the river and turns sharply south, continuing to Lake Champlain, where it may be seen at many places along the eastern shore of the lake. From here the fault line continues southward to Troy and Albany, where it crosses the Hudson River and gradually loses itself in southern New York. The northwesterly moved

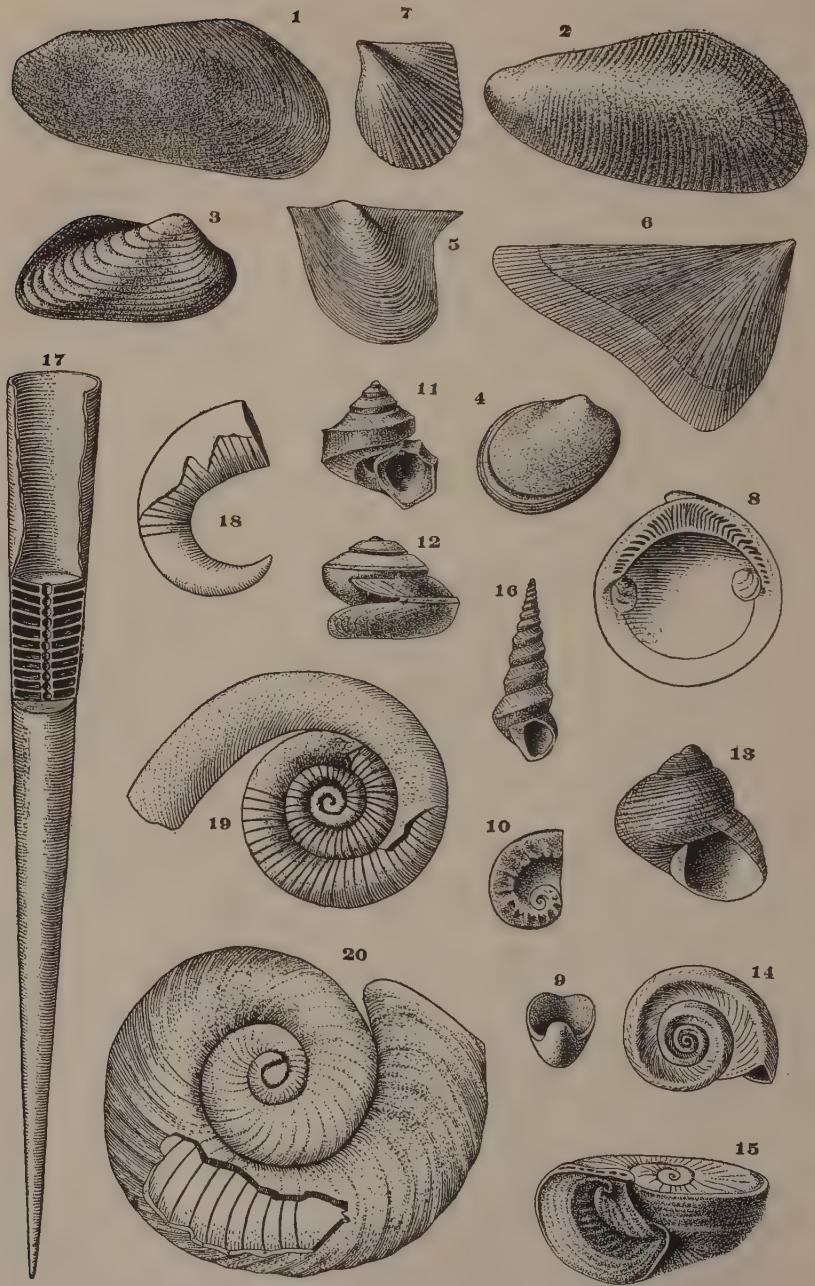


Plate 5. — Ordovician bivalves (1–8), gastropods (9–16), and cephalopods (17–20).

See Appendix B.

mass of Acadia faces the rugged Laurentides, and between them lie the placid St. Lawrence and the remnants of the still horizontal deposits of the Central Interior sea. The great marble quarries of Rutland, Vermont, are like open foundations which permit us to look below the once existing overthrust masses at the limestone floor below. These limestones were laid down by the Central Interior sea and are the continuation of the unmoved remnants along the north side of the St. Lawrence River.

Logan's line is not thought to have been made in Ordovician time, but was one of the major results of the Devonian disturbance (Shickshockian) and the Appalachian Revolution which occurred toward the close of the Paleozoic.

Interior Region. — In the interior of North America the Ordovician seas were, in the main, clear-water ones, depositing calcareous materials and largely limestones. Toward the margins of these seas the sediment was greatly increased by the addition of much mud and some sands. In a broad, general way it may be said that there are in the middle Appalachian region from 6200 to 9700 feet of Ordovician strata, thinning down in the Mississippi valley to, at most, 1900 feet and in many places to less than 1000 feet.

Rocky Mountains Area. — In the Rocky Mountains region the greatest thicknesses are in Nevada and Utah, where there are Ordovician limestones, essentially Lower Ordovician ones, between 3000 and 5000 feet thick. These deposits thin down rapidly northward and also eastward, but in British Columbia they again thicken to the northward, for in the Mackenzie valley there appear to be more than 4000 feet of limestones, dolomites, and shales.

Areas of Greatest Sedimentation. — The limestones are most dominant and in greatest mass in the Lower Ordovician and are essentially magnesian and locally even dolomites. We have here the same geographic position of masses of sediments seen in the Cambrian, a phenomenon that is repeated throughout the Paleozoic, namely, the proximity of the greatest volumes of sediments to the eastern and western land masses (Acadia, Appalachia, Cascadia), while in the northern interior seas the volume is less than one fifth that of the Appalachian trough. The detrital materials came, therefore, from the marginal lands, and very little matter other than that precipitated from solution was derived from the far larger northern land, Laurentia.

Climate of Ordovician Time. — The vast limestone and dolomite accumulations of Ordovician time throughout North America, which have an abundance and great variety of life even in the Mackenzie valley and arctic Alaska, point to warm and equable waters. The same Middle Ordovician reef corals that are found in Tennessee and New York occur also in Baffin Island, the Mac-

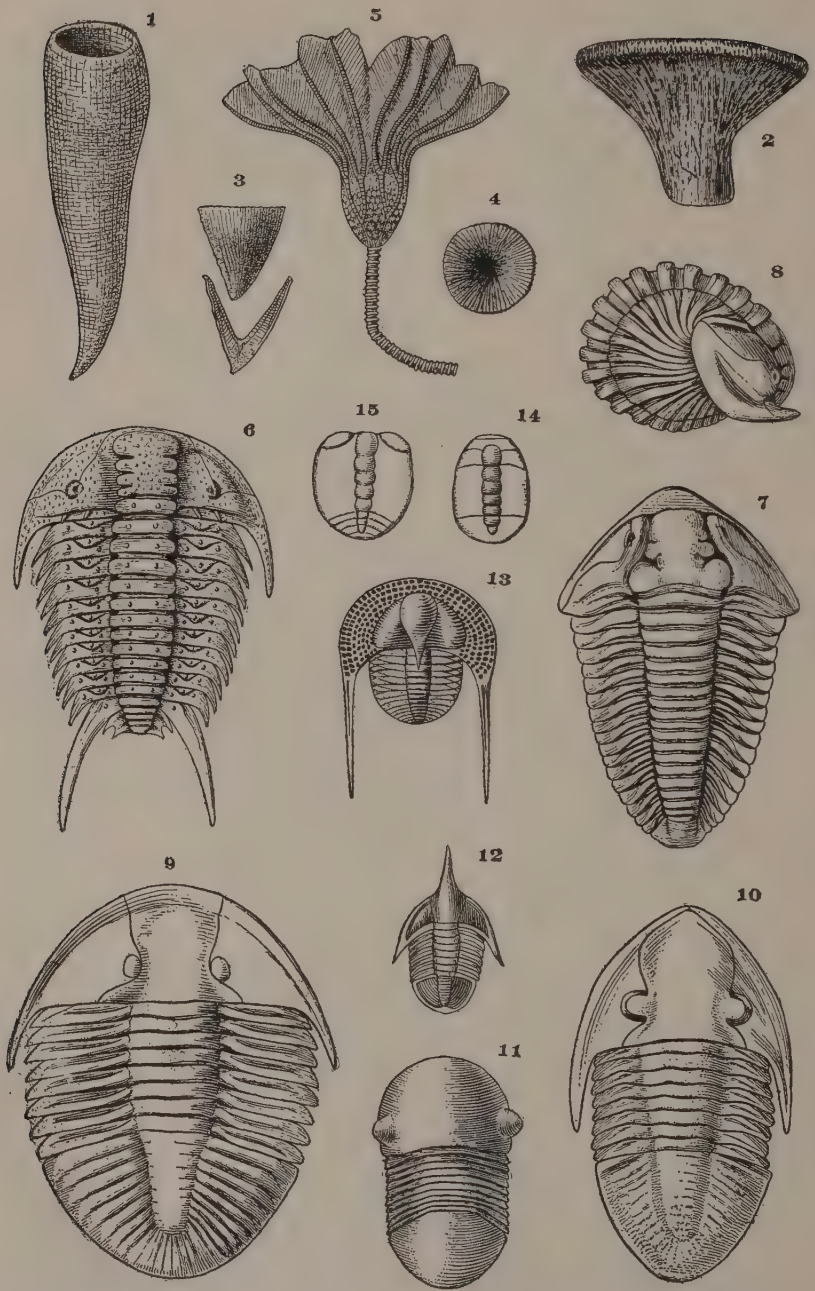


Plate 6. — Ordovician sponges (1, 2), cup corals (3, 4), crinid (5), and trilobites (6–15). See Appendix B.

kenzie River valley, and Alaska, though they are less abundant in the far north. We may therefore assume that the temperature of the lands and the seas in the northern hemisphere was nearly everywhere the same, and that it was warm temperate throughout.

Divisions of the Ordovician Period

Basis for the Divisions. — Partly on the basis of the entombed fossils, but more particularly because of three distinct cycles of continental submergence, Ordovician time in North America is divisible into as many epochs of time, or series of strata. In each epoch the oceans invaded more or less of the land and then withdrew from the continent, if not entirely at least in great part. The first flood, or Canadian, was not of great extent, but the second, or Champlainian, and the third, or Cincinnatian, were the greatest of all Paleozoic time. These three epochs may eventually be recognized as of the value of periods, for the one of Middle Ordovician time had a duration not shorter than that of the Silurian. In that event they will be referred to in North America, not as parts of the Ordovician, but under distinct terms, probably the ones used below.

These three periods or epochs of the Ordovician are further divisible as follows:

Upper Ordovician or Cincinnatian	Gamache Richmond Maysville and Lorraine Eden and Utica
Middle Ordovician or Champlainian (Cambrian of Sedgwick)	Collingwood Trenton Black River Lowville Chazy and Stones River, St. Peter
Lower Ordovician or Canadian	Fort Cassin Beekmantown

Canadian or Lower Ordovician

Definition. — Dana proposed the term Canadian for this epoch in 1874, because, as he states, the strata and fossils were first distinguished and described in Canada by Canadian geologists. In no place has there been determined an unbroken deposition from the Upper Cambrian into the Canadian, but while there is an unconformity between them, it is never of a marked character. In other words, there was no appreciable deformation immediately preceding Ordovician time. The Canadian submergence was restricted to the Acadian area, the eastern United States, and the

Great Basin of Nevada and Utah. In the upper Mississippi valley, during the emergent time, that is, when the lands were dry, Upper Cambrian deposits were apparently exposed to a desert condition, and the sands were blown about, making the rounded sand grains which in the next epoch were gathered together to form the basal sandstone of the St. Peter invasion, now seen throughout the upper Mississippi drainage area. The paleogeography of this time is not yet well enough known to present a map of it here.

Life of the Canadian Epoch. — In the Acadian or Atlantic province the most characteristic fossils of the Lower Ordovician are the first true graptolites (*Tetragraptus* and *Phyllograptus*, see Pl. 4, Figs. 1–4;

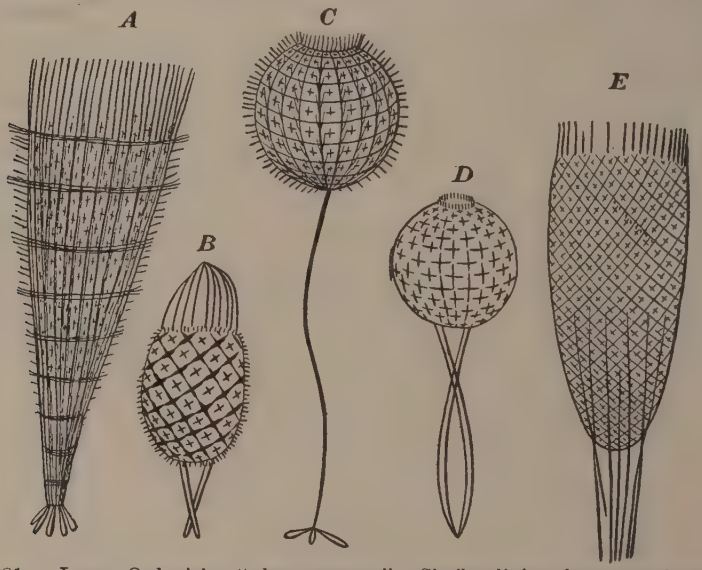


Fig. 381. — Lower Ordovician "glass sponges." Similar living forms are known as "Venus's flower baskets." After Dawson and Hinde. See Appendix B.

for further description of graptolites see Chapter XXXV). Otherwise these strata are poor in fossils, but occasionally most interesting algæ (Fig. 382) and sponges of the type of "Venus's flower basket" (Fig. 381) are found. The Central Interior sea, on the other hand, contained much life, but, on account of the magnesian character of the sediments, the fossils were generally destroyed through the chemical changes that occurred during their deposition. There are here many gastropods, some of them large and thick-shelled, and a variety of straight, bent, and coiled nautilids (see Pl. 5, Fig. 19) as the leading fossils. There are also many trilobites, but it is rare to find a whole one, and usually only heads and tails are seen.

Fig. 382. — Glaciated surface of the "Cryptozoön Ledge" at Lester Park, in township near Saratoga Springs, N. Y. Photograph by H. P. Cushing, N. Y. State Survey.

Champlainian or Middle Ordovician

Definition. — This division derives its name from the Lake Champlain area, where the New York geologists of 1838–1842 first studied and named its formations. It was a long epoch of time and one with much change between land and sea. The waters were oscillatory and variable, with a final great inundation from the Arctic, the first of a series of Paleozoic floods from this ocean. The maximum of the Champlainian submergence occurred early in Trenton time, when the Arctic flood had its greatest extent and seemingly covered about one half of the continent (see Pl. 7). More of Laurentia was then beneath the sea than at any other time since the beginning of the Paleozoic. Our knowledge of the Cordilleran sea of this time is not extensive, but there appears to have been a through waterway from the Great Basin country into the Arctic Ocean. Encroachments by the Atlantic Ocean were restricted to the northeast of the continent and this ocean sent but little of its life into the Central Interior sea. Finally, nearly all of the marine water was largely withdrawn, completing the ebb and flow of Champlainian time, and hence the diastrophic cycle.

Life of the Champlainian Epoch. — During no one of the Paleozoic inundations did the life of the sea record itself so completely by its fossils in the sediments as during the Champlainian epoch. The waters swarmed with a vast variety of invertebrate animals, and there are known more than 1600 species, chiefly of bryozoans (exceedingly small animals, remotely resembling corals), brachiopods, gastropods, cephalopods, and trilobites (see Pls. 4–6). There are about 300 kinds of brachiopods from these deposits in North America, and when the bryozoans are all described there will be nearly 450 species of them. The contribution of the latter as limestone makers, notwithstanding their minute size, Ulrich believes to have been twice as great as that of the brachiopods. There appear to have been as many kinds of gastropods as of brachiopods, but their mother-of-pearl shells were generally destroyed, like those of most of the bivalved molluscs and the nautilids. Trilobites are often common and well preserved and include more than 200 kinds, but in general they are neither large nor ornate (see Pl. 6). There must have been many siliceous sponges (like the glass sponges or "Venus's flower basket," Fig. 381), but, although good fossils of the thick-walled forms (Lithistidæ, Pl. 6, Fig. 2) are common in places, yet, as a rule, the sponges are conspicuous by their absence. Crinids (animals related to the star-fishes but fastened to

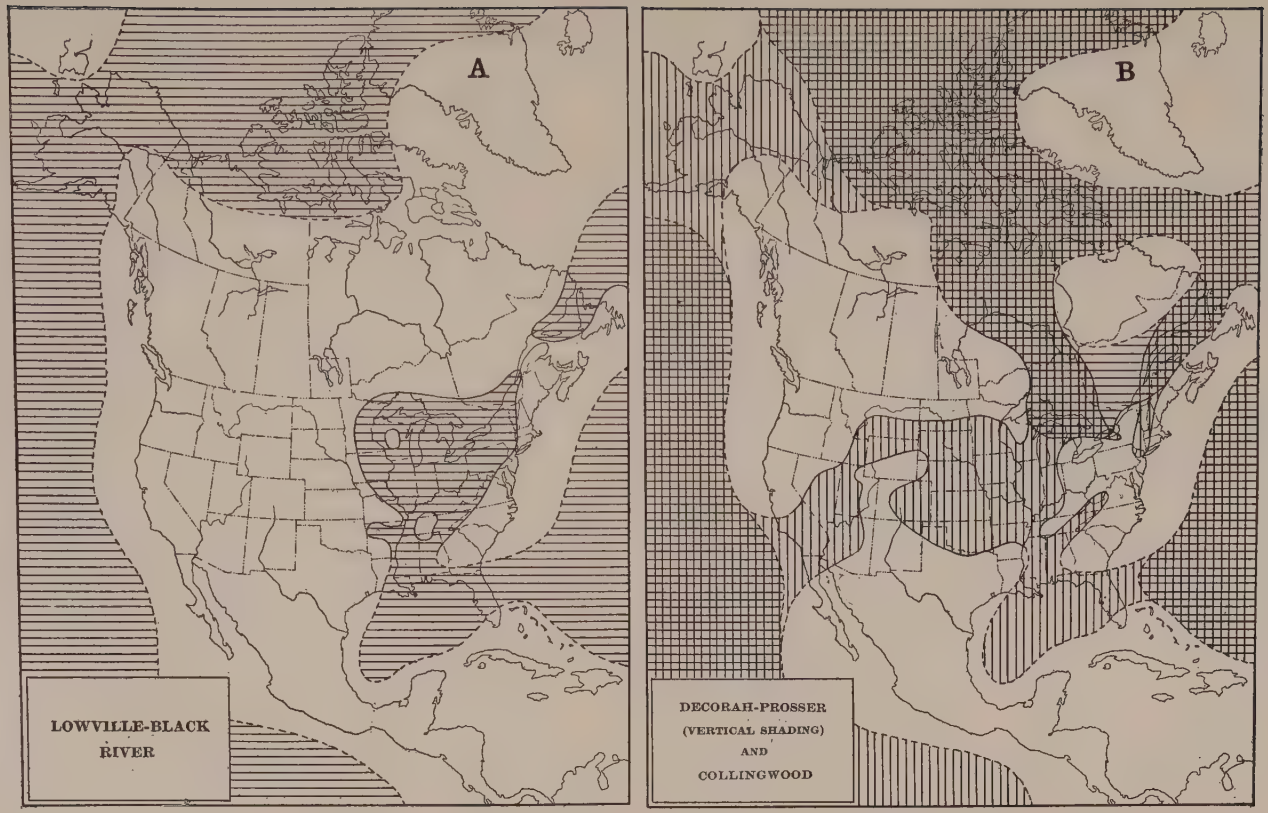


Plate 7. — Middle Ordovician (Champlainian) paleogeography.

the ground by a stalk, see Pl. 6, Fig. 5) are locally common, and contributed largely to the making of limestones. The first true Paleozoic corals appeared here, both cup (Pl. 6, Figs. 3, 4) and compound forms, along with stony hydroids (stromatoporids), and exhibited a tendency to form reefs, but they constituted only small and disconnected colonies. Bivalved crustaceans or ostracods were plentiful and often in large species, and these organisms frequently contributed to the making of limestones.

In Europe the seas of this time were equally prolific in life.

First Vertebrates. — In 1891 Walcott announced the finding of an abundance of fragmentary vertebrate remains in the Ordovician near Canyon City, Colorado, and since then similar remains have been found in the Big Horn Mountains of Wyoming and the Black Hills of South Dakota. These fossils usually occur in a sandstone 6 to 8 feet thick at the base of the Middle Ordovician deposits of the Cordilleran sea. There can be no question that these are the armor bones of fishes of the same type seen often in late Silurian and throughout Devonian time (Ostracoderms). They are described in Chapter XXXVII. From their fragmental nature and their occurrence in sandstones it seems probable that these fishes were inhabitants of fresh waters, and that after death they were drifted by the rivers and broken up before arriving in the marine sediments.

Cincinnatian or Upper Ordovician

Definition. — These formations were first studied in southwestern Ohio and chiefly about Cincinnati, and to the rocks in this region the name was applied by Meek and Worthen in 1865. The Champlainian sea had almost completely vanished from the continent when a new cycle of water movement spread from the Gulf of Mexico northeastward along the western side of Appalachia, northward into the Ottawa basin, and westward into Indiana. This was the sea of Eden and Maysville time (see Pl. 8, Fig. A), a muddier water than that of the two earlier invasions, and it brought back to the interior sea the previous southern faunas that had been changing elsewhere during the emergent interval into other forms. After nearly 500 feet of shales and thin-bedded limestones had been deposited, another flood from the Arctic Ocean arrived, spread its Richmond fauna far and wide over North America and submerged more than 40 per cent of the continent (see Pl. 8, Fig. B).

Life of the Cincinnatian Epoch. — The Cincinnatian faunas were at first very similar to those of the previous epoch, but the Arctic invasion introduced new types of animals which gradually changed

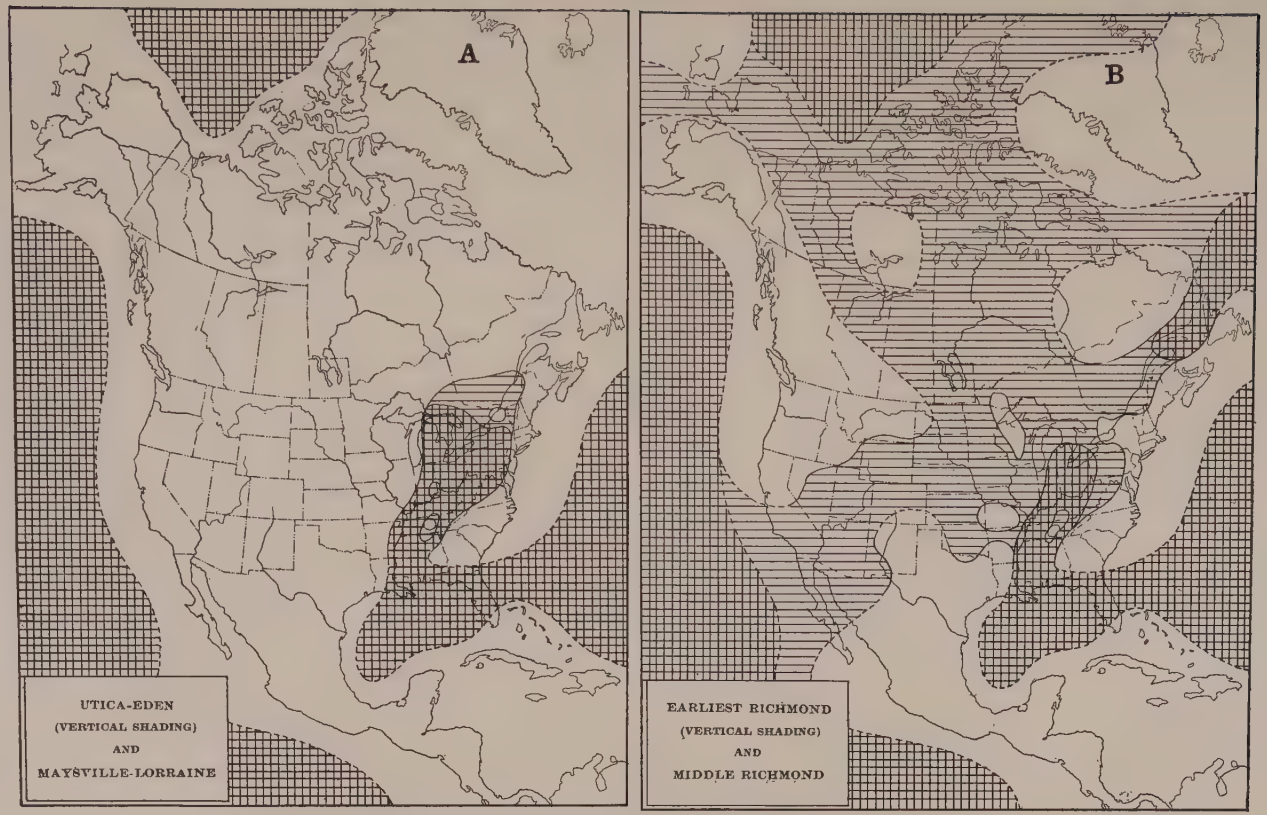


Plate 8. — Upper Ordovician (Cincinnatian) paleogeography.

into others prophetic of Silurian time. These differences are seen more especially among the bryozoans, brachiopods, and corals. However, there is still so marked an Ordovician stage of organic development present in the faunas of the Cincinnatian series as to compel its association with the Champlainian, rather than with the Silurian.

Taconic Disturbance

Cause. — From a study of the paleogeography of Middle and Upper Ordovician time, it is seen that the seas were undergoing much change. This unrest in the hydrosphere was apparently due to movements within the mass of the North American continent, not only depressing and elevating the land but affecting the general level of the strand-line as well. We have seen that the greatest mass of sediments was laid down adjacent to the marginal lands Acadia, Appalachia, and Cascadia, and here, therefore, occurred the greatest depressions of the original land surfaces. In eastern Pennsylvania this maximum sinking was over 15,000 feet during Cambrian and Ordovician time, and it was about the same, or even 1500 feet greater, along the eastern side of Lake Champlain. In the Great Basin area of the Cordilleran sea the sinking of the bottom during the Early Paleozoic was also great, being over 16,000 feet. Such depressions naturally must have set up great stresses that were of gradual accumulation within the mass of the continent, and particularly underneath the areas within and closely adjacent to the geosynclines. Finally, when the stresses attained the breaking point, relief was obtained by readjustments deep within the continent, which also altered the surface topography. This relief was greatest in the northern Appalachian geosyncline, where the Cambrian and Ordovician sediments accumulated, for these strata were raised during the later Ordovician into a mountain range of which the present Green Mountains in western New England and their southern extension, the Taconic Range, are but recently reëlevated western remnants. Dana in 1874 called this disturbance the *Green Mountain Revolution*, but in his text-book of 1895 refers to it as the *Taconic Revolution*.

Cincinnati Uplift. — Long before these eastern mountains became a marked topographic feature, the subsidences within the geosynclines also warped the bottoms of the continental seas and affected their depth, area, and outline. Some of this warping was manifested in the Cincinnati uplift, the southern end of which came first above the sea, for early in Middle Ordovician time (Lowville)

appeared *Nashville island.* This initial uplift then slowly moved northward and reached the area north of Cincinnati before the close of the Trenton. (The axis of this uplift is shown in Fig. 365.) However, the uplift did not remain as yet as a permanent surface feature, for Nashville island was again beneath the sea when the Cincinnati area emerged. With the birth of the Taconic Mountains the Cincinnati uplift attained permanency and became a topographic feature of the subsequent Paleozoic seas.

Metamorphism. — In Vermont, the Cambrian and Ordovician sandstones are now quartzites, the shales are slates, and the limestones are marbles. This change took place when the strata were folded, particularly during the Appalachian Revolution (page 748). Some of the metamorphism, however, may be connected with the rising of the White Mountains of New Hampshire in Devonian time (page 699).

Main Area of Disturbance. — The greater part of Acadia was affected by this disturbance, for the subsequent rocks are seen to rest in most places with an angular unconformity upon the older strata. Such contacts can be seen to advantage at Gaspé, Quebec, where the nearly vertical Ordovician strata have been eroded to a horizontal surface on which repose Lower Devonian limestones. Exactly the same conditions are seen at Becraft Mountain southeast of Hudson, New York, while at Otisville in the same state, but near the New Jersey state line, the angular unconformity between the Middle Ordovician and basal Silurian sandstones (Medina) is not over 15° (see Fig. 397). Unconformities between the Ordovician and later strata are general in Nova Scotia and New Brunswick. We see, therefore, that all the land from the Gulf of St. Lawrence down to at least New Jersey had been thrown into folds, and it is probable that the present Taconic Mountains are but the western member of a series of ranges with similar trends, for it is known that the Silurian, and especially the Lower Devonian, seas entered Acadia in a set of narrow troughs.

Economic Products

Mineral Oil and Gas

Nature of Natural Hydrocarbons. — Natural hydrocarbons, that is, compounds of hydrogen and carbon, are present in all sedimentary rocks of marine origin that are not too much metamorphosed, and while they are also undoubtedly stored in sediments of fresh-water origin, no valuable deposits in such have so far

been found. The greatest amount occurs in a disseminated condition in the shales, especially in the fossiliferous black shales, where oil forms as much as 21 per cent of the rock mass. Even when only 3 per cent of the rock is petroleum it can be extracted by heating the shales and driving off the crude oil, and was so produced many years ago at a cost of 14 cents a gallon. Impure limestones, especially when dark in color, are full of oil, a fact at once noticeable on fracturing them with a hammer, when the odor of petroleum becomes apparent. Even if a rock series 1500 feet thick had but 0.001 of 1 per cent of petroleum, this amount would yield 750,000 barrels to the square mile, an amount nearly equal to the greatest actual production per square mile of any part of the leading Pennsylvania fields (Orton). However, if the material is to be commercially valuable, it must be concentrated by natural agencies into limited underground areas and such invisible reservoirs must be discovered by the driller, but these valuable accumulations are not of common occurrence. The natural hydrocarbons occur in the sedimentaries in all conditions from natural gas through light oil and heavy oil into asphalt. For the distribution of the oil and gas fields in the United States see Fig. 383.

Original Source of Hydrocarbons. — The hydrocarbons in the main result from bacterial decomposition of organic material, and chiefly from animal remains undergoing reduction on the sea floor. That they are of organic origin is proved by the fact that they have the same optical properties as animal oils. Microscopic globules of oil result from the bacterial change and have a very decided affinity for tiny flakes of mud suspended in the water. When there is much rapid organic destruction going on in muddy waters of little or no circulation, there results a more or less decidedly petroliferous shale, or a dark impure limestone, but in clear water and in agitated seas most of the hydrocarbons escape into the air.

Storage of Oil and Gas in Nature. — Oil and gas are segregated into reservoirs or " pools " in porous rocks which in most cases are sandstones or conglomerates, and more rarely crystalline dolomites (see Fig. 421). This concentration seems to be due in most cases to percolating waters that are now, or were formerly, within the sediments and which, by their movements, drive the disseminated oil out of the rock. The latter, being lighter, gathers at the top of the water, and if this is under hydrostatic pressure the compressed gases coming from the oil are driven to higher levels until stopped by a thick shale stratum, for shales are practically impervious to water, oil, and gas. When the rocks are devoid of water, in which

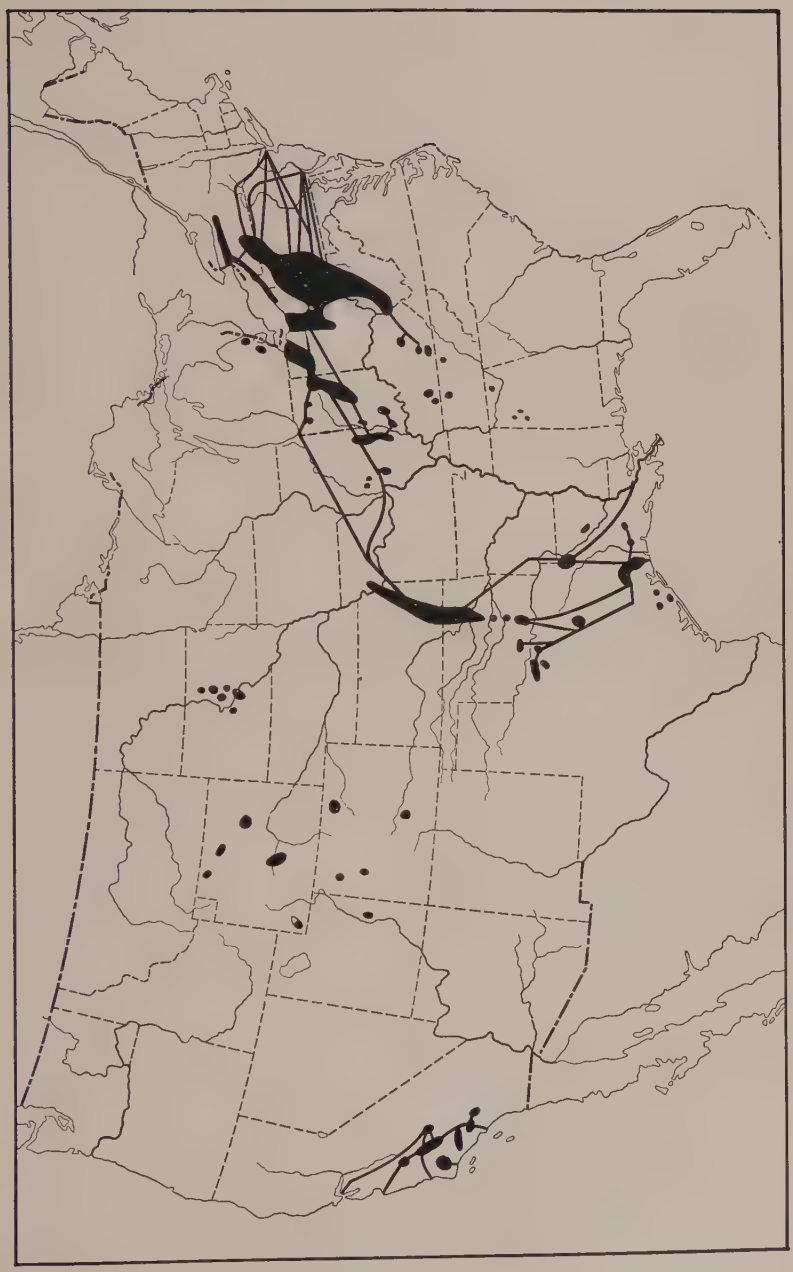


Fig. 383. — Map showing in generalized form the main oil and gas fields and pipe-lines in the United States. Redrawn from a large and detailed map published by the U. S. Geological Survey.

case they are said to be " dry," the gas separates from the heavier oil and rises to higher levels of the rock beneath the shale cover, while the oil gravitates down the dipping slopes of the strata to lower levels and segregates in the more porous areas, where oil " pools " are formed. The pools in dry strata are more irregular in distribution than those in wet formations. When a large quantity has concentrated there seems to be a tendency for the pools to seal themselves at the top, and, if more and more oil and gas are added from below, the " rock pressure " rises above the hydraulic pressure or " head " produced by the water of circulation. Lower " rock pressures " are the rule, from 350 to 500 pounds to the square inch, but they are known up to 1525 pounds to the square inch (in gas wells). Hydrocarbons may also be driven to higher levels by the heat of subterranean bodies of intrusive igneous rock, or by chemical alterations within the strata, but such fields are the exception.

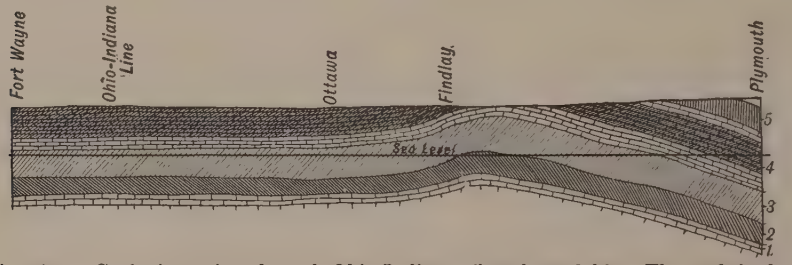


Fig. 384. — Geologic section through Ohio-Indiana oil and gas fields. The arch is the Cincinnati uplift. 1, Trenton limestone, the oil and gas horizon; 2, impervious shales of the Ordovician (Utica and Eden); 3, Cincinnatian; 4, Silurian limestones and dolomites; 5, Devonian limestone and shales. After Orton, U. S. Geol. Surv.

Geologic Structure of Oil and Gas Areas. — Oil and gas are usually found in the flattened tops of depressed geologic arches and down the slopes of anticlines where the dip of the strata is arrested so as to form shelves or terraces (the " terrace structure " of oil experts), but there is always above the productive zones an impervious and usually a thick shale cover. Broadly stated, the thicker the shale formation, the more impervious the cover, and the deeper the storage bed, the richer the gas or oil field (Fig. 384).

Trenton Oil and Gas of Ohio. — The oil and gas of Ohio and Indiana are stored in the upper 20 to 30 feet of the Trenton dolomite, in places where it is highly crystalline and therefore very porous, and at depths of from 1100 to 2200 feet below ground (Fig. 384). The black to brown Utica shale, hundreds of feet thick, forms the impervious cover. Below the oil and gas there is always

highly saline water. The oil and gas fields are connected in the main with the "terrace structure" of the Cincinnati uplift and are situated under its northern end, and under the short northeasterly trending arch known as the Lima spur of Ohio and the broader northwesterly trending arch known as the Wabash spur of Indiana. The once famous Karg gas well of Findlay, Ohio, stood on the edge of a rapid descent of the Trenton dolomite; and only a thousand feet west of it, where the top of this formation lay 120 feet lower, the adjacent well yielded petroleum.

Discovery of Oil and Gas in Ohio. — As far back as 1836 natural gas was known to escape freely from the ground in the vicinity of Findlay, Ohio, and for a long time a few very shallow wells were covered to collect the gas for domestic use, but only Doctor Oesterlin, after 1862, suspected that great reservoirs of it were stored deep in the strata. It was not until 1883, however, that he finally succeeded in forming a company to drive the "Pioneer Well," which yielded Trenton gas at a depth of 1092 feet beneath the surface. *This has been regarded as one of the most important discoveries in Economic Geology of the past century.* The daily flow of gas from this well was 250,000 cubic feet. Before the close of 1886 three great gas wells were found: the Karg well, giving 14,000,000 cubic feet of gas per day; the Simons well, 12,000,000; and the Van Buren well, exceeding both with 15,000,000. Artesian oil wells were also soon found yielding hundreds of barrels per day, and exceptional ones with a daily flow of 1000 and even 5000 barrels per day. Ohio then became alive to its underground wealth and an oil and gas excitement spread throughout the state. The fever spread to Indiana, and this state became an even greater gas producer, with a daily yield in 1890 of 780,000,000 cubic feet. Entire industries, such as that of glass making, moved at this time to central Indiana because of the cheapness and easy adaptation of this fuel.

Even though it was soon learned that wells lasted at most but several years and then declined rapidly to extinction, tremendous waste occurred. Nature's great wealth of long accumulation was soon dissipated, though the period of Indiana and Ohio's gas prosperity would have lasted several times as long under wise protection against wastage. I. C. White has stated that the gas and oil wasted in the United States during 1908 was roughly equivalent in fuel to the heat yielded by one billion bushels of coal!

Annual Yield of Oil and Gas in the United States. — The yield of petroleum in 1913 in this country was 248,000,000 barrels, valued at $237,000,000. The value of natural gas for the same year was $88,000,000. Eighteen states have yielded since 1859, when oil was "struck" in Pennsylvania, 3,000,000,000 barrels of petroleum, valued at $2,575,000,000.

Other Economic Products

Limestone, Marble, and Cement. — Because of the wide surficial distribution of the Ordovician limestones they are much quarried for foundation structures, road metal, flux for the reduction of iron ores, and especially for the lime used in mortar, whitewash, and fertilizer for farm land. In the Appalachian valley they

are also much used in the making of Portland cement. In Vermont there are immense quarries in the Lower Ordovician from which is obtained most of the American Carrara, or white and clouded marble. In eastern Tennessee some of the Middle Ordovician fossiliferous limestone is mottled pinkish to deep red in color and is used for decorative and interior purposes.

In the United States in 1913 there were 113 plants making Portland cement. During this year they made over 15,000,000 long tons, valued at $92,000,000.

Lead and zinc, mainly in the form of sulphides and carbonates, have been mined for more than a century and in considerable quantity from the Middle Ordovician dolomites of eastern Iowa, southern Wisconsin and northern Illinois; the formation from which they come is known to geologists as the Galena formation, and is of the same age as the Trenton of New York. The ores occur in solution cavities, in crevices, or as replacements of the limestone. Some lead is also yielded by the Upper Cambrian of the Ozark region of Missouri and Arkansas.

Calcium phosphate, valuable as a fertilizer, is obtained in central Tennessee, where the limestones are rich in the tiny gastropod shells (*Cyclora*) mentioned on page 619.

CHAPTER XXXV

ANIMALS WITH RADIAL SYMMETRY

Radial and Bilateral Animals. — Among the lowly organized invertebrates there is a vast variety in which the outer form and the arrangement of the organs are seemingly not bilaterally planned, as in most animals. In this group, instead of the halves on each side of an imaginary median line having the same structure but arranged in an opposing way, the two parts being left- and right-sided, the symmetry is radial, the parts radiating from the central mouth and body sac. The naturalists of the early part of the nineteenth century grouped all animals with such symmetry under the name *Radiata*. Later it became apparent that their radiate structure was often only superficial, and that most of them when young were built on the bilateral plan; in other words, that radial symmetry in mature animals did not necessarily indicate blood-relationship. This classification of animals based on superficial resemblances naturally had to be given up, but nevertheless the description " animals with radial symmetry " is applicable in a broad way to many invertebrates and helps the beginner in Historical Geology to understand their fundamental adult structure. The radiate form is probably largely due to the sedentary and sluggish habits of the animals which possess it, and it is all the more readily brought about because of the absence of a definite head region.

Types of Radiate Animals. — Animals with radial symmetry are now classified into two wholly independent divisions. The more simply formed or primitive one is the stock (phylum) *Cnidaria*, or *Cœlenterata* (cœlenterates), the latter name implying that the animals have but one internal cavity which serves both as a body cavity (cœlome) and as a digestive cavity or sac (enteron). All higher animals, on the contrary, have two cavities, a true body one which may contain the internal organs, such as the heart and lungs, and within this another independent digestive cavity, such as the stomach or intestine. These higher animals are known as cœlomates. The cœlenterates are, as a rule, very simple animals in which appear the beginnings of definite organs. In their variety

they seem nearly to exhaust the possibilities of radial symmetry, and many are very flower-like. They have, therefore, also been called zoöphytes (plant-animals), and in their budded colonies afford interesting illustrations of coöperation and division of labor. Practically all of them live in the sea. In the Cnidaria the secretion of an external skeleton composed of carbonate of lime is not the rule, although it is marked in some stocks, as, for instance, among the corals.

The second division is the phylum *Echinodermata*, including animals that generally have marked superficial radial symmetry, but as they have the true body cavity, and are, therefore, cœlomates, they cannot be grouped under the old term Radiata. The Echinodermata and Cœlenterata as differentiated above are brought together in this chapter for easy reference. There is in the former a more decided tendency to form calcareous skeletons. In the very young or larval stage these animals are distinctly bilaterally symmetrical, and are placed higher in the scale of animal life than the Cnidaria. Echinodermata are exclusively marine and are of great diversity of external form.

The following table presents briefly the kinds of animals having a radiate structure:

Phylum **Cnidaria.** Marine animals that are free or attached to the ground. They live as individuals or are combined into colonies, and they may have a skeleton that is either horny or of carbonate of lime.
- Class **Hydrozoa** or hydroids. Simplest and least known Cnidaria.
  - **Graptolites.** Ancient hydroids with horny skeletons.
- Class **Anthozoa** or coral animals.
  - **Sea anemones.** Individual coral animals without skeletons.
  - **Stony corals.** Corals with skeletons of carbonate of lime.
    - **Archæocyathidæ.** Primitive individual Cambrian corals.
    - **Tabulata.** Paleozoic colonial corals without true septa.
    - **Tetracoralla.** Paleozoic individual and colonial corals with septa.
    - **Hexacoralla.** Post-Paleozoic corals with septa.

Phylum **Echinodermata.** Marine animals usually with an external skeleton of carbonate of lime, made up of many pieces.
- Class **Stelleroidea.** Starfishes. Free animals.
- Class **Echinoidea.** Sea-urchins. Free animals.
- Class **Crinoidea.** Attached feather-stars.
- Class **Blastoidea.** Attached nut-like animals or pentremites.

Corals and Coral-like Animals

(*Phylum Cnidaria*)

General Description. — In the living world there is a vast group of diverse, radially symmetrical, marine animals that the zoölogist speaks of as Cnidaria (from the Greek for *nettle*), because the great

majority of them have the power of stinging. This stinging is done by a multitude of very minute threads, each one of which is shot out of a cell buried in the skin and enters any soft body that comes into contact with the animals (Fig. 385). More of the stinging cells may be connected with the internal cavity, where they are a part of long filaments attached to the inner edges of the mesenteries or the vertical partitions (septa).

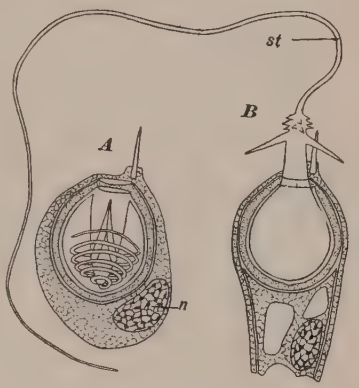


Fig. 385. — Stinging or nettle cells of *Hydra*. Greatly enlarged. After Schneider. *A*, undischarged cell, note trigger hair. *B*, discharged cell with the poisonous thread (*st*) released. *n*, nucleus.

In general, it may be said that Cnidaria are very primitive animals whose body is a sac with the closed end attached and the other free, the widely distensible opening being the mouth. Into it is passed the food, which is digested in a more or less simply constructed cavity of the sac, and through the same opening is ejected any indigestible remainder. They feed, as a rule, on the smaller animals, but when the individuals, or polyps, as they are called, are minute, their food consists of microscopic animals or plants. Around the mouth are situated radially a number of hollow, finger-like tentacles and much of this tentacular end, or even the entire outer surface, is covered with innumerable stinging cells.

The microscopic stinging cells have a flask-shaped cavity containing a long, delicate, coiled thread immersed in a more or less poisonous fluid (see Fig. 385). On the outside of the cell there is a minute trigger-hair, a very delicate sensory organ, which, when touched, causes the cell to burst and thrust out violently the long thread, thus serving as an organ of defense against enemies and as a means of capturing small animals for food.

Jellyfish or Medusæ. — There are two widely different kinds of Cnidaria individuals: the attached polyps just described, and the free individuals or medusæ, widely known as swimming-bells or jellyfish (Fig. 386 *A* and *B*). The medusæ are very soft, disc- or bell-shaped animals with the mouth and stomach hanging from the under side of the bell, while around its edge are the stinging tentacles. As the medusæ are from 95 to 99 per cent water they are very seldom preserved as fossils and therefore have little significance in Historical Geology and need not be further considered.

Divisions of Coral-like Animals. — There are many types of Cnidaria, not all of which have hard parts, but in this connection only the more important forms need be studied, those that have skeletons either of chitinous (nitrogenous) or calcareous material. The Cnidaria are divided into two classes, the Hydrozoa and the Anthozoa.

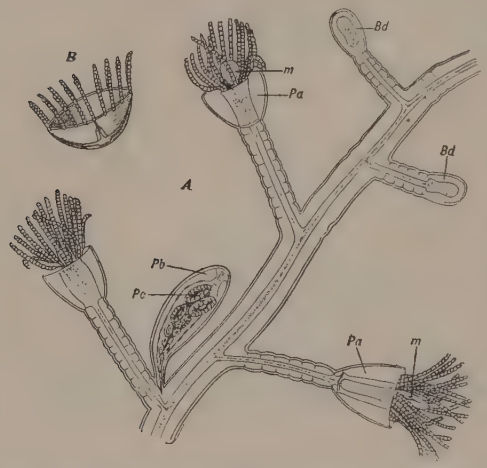


Fig. 386. — Hydroids. *A*, small part of an unsexed, attached hydroid colony (*Obelia*). Much enlarged. *B*, sexed and free medusa stage, with tentacles arranged around margin of umbrella. About nat. size. *Bd*, buds developing into polyps; *m*, mouth; *Pa*, feeding polyps with tentacles extended; *Pb*, reproductive polyp developing medusæ (*Pc*).

Hydrozoa

Hydrozoa or hydroids (named after the nine-headed dragon of Greek mythology, because of the many polyps) usually have chitinous external skeletons and a digestive cavity or cœlenteron which is undivided and relatively simple in that the walls of the sac are not folded or ridged. The mouth is rounded. The polyps live singly or are united into colonies with the members connected with one another. In the colonial forms there is often a division of labor, some being nutritive members, others reproductive members, and so on. The hydroids of most interest in Geology are the extinct graptolites.

Graptolites (from a Greek word meaning *to write*, because the fossils resemble writing) were linearly arranged colonial hydroids with thin chitinous tubular buds, one end of which was fastened to a rod-like axis (see Fig. 387 *A* and Pl. 4). The polyps were arranged in a single linear series (monograptids, Pl. 4, Fig. 6) or there were two series back to back against the axis (twin-graptids, Fig. 7) or even four series with the rod in the center (leaf-like graptids, Pl. 4, Figs. 1–3). A variable number of such colonies were fastened by rods (*virgulæ*) to a float or swimming bell from which they hung; in this way they were freely suspended in the water and drifted along with the sea currents. These were the true or free graptolites, the forms that have much significance in Stratigraphy because the species were common only for a limited time and were scattered widely by the oceanic currents.

Another group of these animals, known as the *dendroid* or net-like graptolites, were of very different habit, being attached either to seaweed or to the sea bottom (see Fig. 387 *B*). These polyps did not have the axial rod but were arranged on flexible, more or less

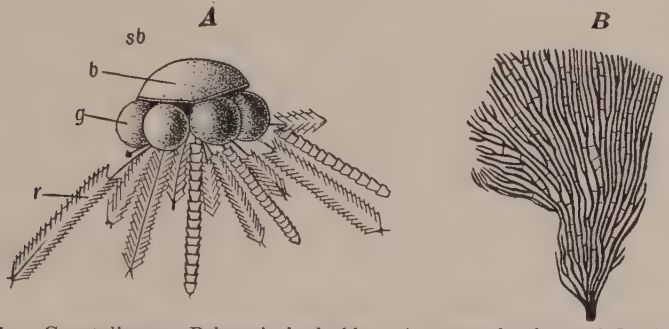


Fig. 387. — Graptolites or Paleozoic hydroids. *A*, restored colony of floating type (*Diplograptus pristis*). Somewhat enlarged. After Ruedemann. *b*, swimming bell; *g*, gonangia or brooding organs; *r*, a branch (rhabdosome) of many polyps in two ranges. *B*, dendroid type of anchored graptolites (*Dictyonema crassi-basale*); the polyps are microscopic and like those in *A*. After Bassler.

irregular branches united to one another by cross-bars. The colonies grew fan-shaped or irregularly funnel-shaped. As a rule, all graptolite fossils are black and they are most frequently met with in black shales.

The dendroid graptolites appeared in the Ordovician and persisted into the early Mississippian but were most abundant in the Ordovician and Silurian. The true graptolites were practically restricted to the two last named periods, while the monograptids were especially abundant in, and characteristic of, the Silurian.

Fig. 388. — A sea anemone, with tufts of tentacles about central mouth. After Emerton.

Anthozoa

The Anthozoa or flower animals include the sea anemones and corals. They are attached polyps whose internal cavity has hanging down in it a rudimentary, tubular, digestive gullet, opening upward into an elongated mouth and below into the true digestive cavity or *cœlenteron* (see Fig. 389). The wall of the latter is not simple as in the Hydrozoa but has a number of longitudinal folds or ingrowths of the body wall projecting more or less deeply into the cavity. When one of these polyps is cut transversely the folds

or partitions are seen as radii, for which reason they are also known as ray animals (Fig. 389). When a hard supporting skeleton or stony part, known as the corallum, is present, as is most often the case, it is usually made of calcium carbonate (see page 171), is nearly always secreted by the outer layer of the soft body, and has its exact form. Therefore the skeletons of corals have an internal radiate or partitioned structure never seen in the Hydrozoa, and it is only this lime skeleton which is preserved in the fossils. The polyps either live singly and are then cylindrical or conical in shape, or more commonly form colonies by the budding of closely adjoining individuals.

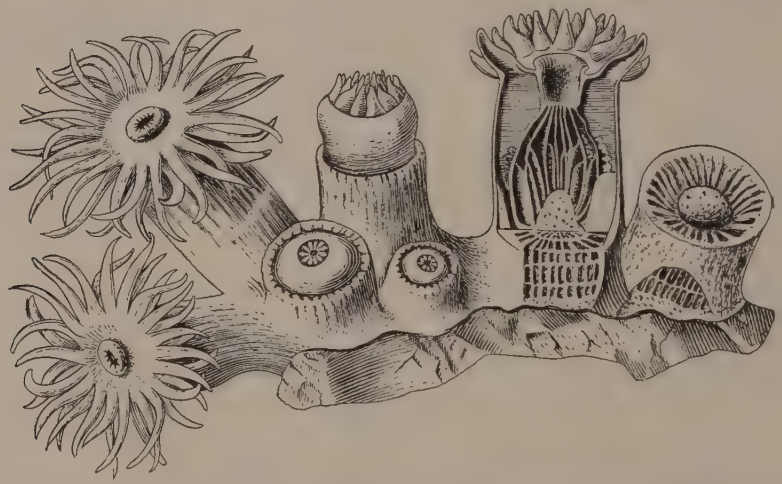


Fig. 389. — Colony of living stony corals, with two individuals fully expanded and feeding, and three individuals retracted and resting. On the extreme right is seen the skeleton of an individual and beside it an individual cut through the center to show the relation of the soft parts to the skeleton, the mouth opening into the gullet, and the large digestive cavity with its many mesenteries. After Pfurtscheller, from Boas's *Lehrbuch der Zoologie*.

They are often brilliantly colored. The polyps known as sea anemones have no skeleton (Fig. 388), but the corals, as a rule, secrete one of calcium carbonate and are therefore called "stony corals," though a few have horny black skeletons and are known as "black corals." The animals that build the stony skeletons are usually very small (under one fourth of an inch), though some kinds attain a diameter of an inch or more, and the sea anemones may even exceed 8 inches. The colonial skeletons may be of any size up to 15 feet across and in height.

Stony Corals. — Cup corals, which are the calcareous bases of single polyps, are of very frequent occurrence in Paleozoic rocks.

They multiply by sexual reproduction and not by budding, as is the case in compound forms. Cup corals are usually conical and more or less curved, with variably deep cups divided into many shallow compartments by radially arranged partitions called septa (see Fig. 390). These septa originate in the outer wall and are of variable length, the several lengths being disposed in a regular manner; only a part of them, the primary septa as a rule, meet in the center, where they often form a simple or twisted column, the columella. The compound corals have about the same general structure as the single polyps, but when closely crowded the corallites take on a prismatic form (see Fig. 391). They may also be circular in outline and then the spaces between the individuals are filled with a loose structure.

Fig. 390. — Paleozoic cup tetracorals. *A*, common Devonian form (*Heliophyllum halli*), with ornate septa. *B*, Silurian form (*Zaphrentis umbonata*), with deep cup, many septa, and a fossula. *C*, Devonian species (*Amplexus yandelli*) sectioned to show tabulæ. After Rominger.

The types of coral structures most often seen fossil are the following:

Archæocyathidæ or archeocyathids (primal cup corals). — These are the most ancient and the simplest corals known and are restricted to the Lower Cambrian (see Pl. 1, Figs. 5, 6). All are single polyps, the corallum being a more or less long cone, sometimes reaching 11 inches in length, nearly straight, and with one end tapering to the point of attachment. Commonly these corals are, however, under 3 inches in length. The outer wall may be thick and porous or with worm-like canals, or there may be two thin walls united by longitudinal, radially arranged septa. The basal por-

tion of the corallum is also more or less thickened by vesicular partitions. The living chamber is very large and deep, sometimes reaching almost to the bottom of the corallum, and is devoid of septa throughout, a condition of primitiveness seen in no other corals. Furthermore, the walls in most forms are regularly perforated by comparatively large pores arranged in longitudinal series, another character not seen in other corals and one whose purpose is not yet understood. For their wide distribution, see the chapter on Cambrian time (XXXI).

Tabulata or tabulate corals (*tabula* means *bottom* and has reference to the many transverse partitions found in the tubes). — These specialized Paleozoic corals always grow in colonial form, and, as a rule, the individual polyps are very small or even minute transversely, but longitudinally they build more or less long tubes

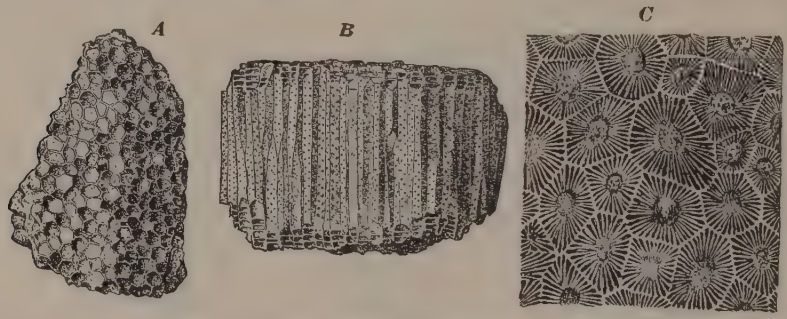


Fig. 391. — Compound Devonian corals. *A*, tabulate or honeycomb coral (*Favosites polymorphus*). *B*, same, from the side, to show transverse partitions (tabulæ) and small mural pores. *C*, transverse section through a tetracoral (*Cyathophyllum rugosum*), showing close union of individuals, and radial septa.

that are abundantly partitioned by tabulæ as the animals grow upward (see Fig. 391 *A* and *B*). The polyps may be loose in growth when the individual corallites are round or oval in outline, but more often the tubes are tightly appressed to one another and the corallites uniformly prismatic. There are no radial septa and when such appear to be present they are seen to be a series of short spines arranged in longitudinal rows (incipient septa, as it were), or the spines may be irregularly disposed. The walls of the corallites are thin and perforated by large pores, the mural or wall pores (see Fig. 391 *B*), which represent failures at budding for the reason that almost no space is present for the vast majority of the possible buds to grow into individuals.

The tabulate corals appeared in the Middle Ordovician and had their greatest development in the Silurian and Devonian.

The chain coral (*Halysites*, Pl. 9, Fig. 1) was characteristic of the Silurian and Ordovician, while the honeycomb corals (*Favosites*, Fig. 391 *A* and *B*) were great reef makers in the Silurian and Devonian, where some of the colonies had a diameter of 4 feet. The organ-pipe-like coral (*Syringopora*, Pl. 16, Fig. 8) was common throughout the Silurian and most of the later Paleozoic time.

Tetracoralla or tetracorals (corals with the septa arranged in four quadrants). — Throughout the Paleozoic from Middle Ordovician time, and more especially beginning with the Silurian, the tetracorals are common fossils (see Figs. 390 and 391 *C*). Cup corals were very common in the Middle Paleozoic and were more numerous, in greater variety, and of larger size (up to 2 feet long) than those of subsequent times. Compound tetracorals were also abundant, and, with the cup corals, were of wide distribution, being especially common as reef makers in the Silurian and Devonian. They were rare in the Pennsylvanian and passed out of existence with the Permian.

In the cup tetracorals the bundling of the septa is usually readily seen, and with their smooth or somewhat wrinkled exterior covering (*epitheca*) extending from the base to the edge of the cup, they are easily distinguished from other kinds. The compound tetracorals are usually not so easily separated from the Hexacoralla (six-rayed corals), because the tetramerism or division into four parts is much or wholly obscured, but, as a rule, it is seen that the polyps are larger while the radial septa are more numerous or at least thinner, straighter, and simpler. Some of these compound tetracorals attain the size of modern colonies and have been seen as large as 12 feet across.

Hexacoralla or hexacorals were the common kinds after Paleozoic time and are the main reef builders of the present oceans. The name has reference to the fact that the young polyps start with six primary septa and all subsequent cycles of partitions are regularly introduced between the previous ones. There is, therefore, a regular radial arrangement of the septa and they are never bundled into quadrants as in the Tetracoralla, and the single polyps are also not so decidedly cup- or funnel-shaped. In the compound forms the animals are apt to be small, often very small, as in the staghorn corals, while the corallites are not, as a rule, so distinctly walled from one another as are the older corals. The walls often also appear to be thick, and in many forms the individuals are compressed and seem to merge irregularly into one another, suggesting the convolutions of a mammal brain, hence the name brain-corals, which is sometimes applied to them.

Habitats of Living Corals. — Hexacorals live in all oceans from sea-level down to 11,000 feet, but are particularly common in clear tropical waters and in depths of less than 240 feet. In the deeper, darker, and colder waters the single polyps predominate, while on the reefs where the sunlight is strong the compound corals are most prolific. There are five times as many kinds of hexacorals in waters not over 150 feet deep as there are between this depth and 240 feet, the maximum depth to which any reef species extends. Between 600 and 2400 feet there is another coral zone, usually of small single polyps or of delicate, branching, compound forms. Beyond the latter depth corals are few in number and variety and those that do exist are small and extremely fragile. Off the eastern coast of North America between Cape Hatteras and Newfoundland there are known to be living fourteen species of corals, several of which go below 6000 feet (Verrill). Hemispheric corals are known to attain to 15 feet in diameter, while staghorn colonies are reported growing to heights of 15 feet.

In regard to the temperature, strictly reef-building corals flourish only between 68° and 78° F., but will continue to live even at 85° F. The deeper coral zone has a far lower temperature, one between 40° and 50° F., and the deep-sea species may live in water as cold as 32° F. In regard to the nature of coral reefs and the places of their growth, see page 171 and the following pages. A view of a living coral reef is shown in Fig. 145.

Spiny-skinned Sea Animals

(*Phylum Echinodermata*)

General Description. — In the seas and oceans there is a great variety of radiate animals called echinoderms, which means *spiny skin*, a name given because their outer surface is usually more or less studded with parts composed of carbonate of lime in the form of spines and plates. These hard pieces may consist of small particles loosely dispersed in the skin, or occur in the form of spines that make a loose or open mesh, or entirely encase the soft parts in a firm skeleton, a mosaic of closely adjoining plates that are either plain or studded on their outer surface with more or less long spines.

The parts of the body are usually arranged on the plan of five divisions, five radii and the same number of spaces between them — the interradii — being characteristic of the echinoderms. These parts are best seen in the starfishes; while they are present in nearly all Echinodermata, they are at times much obscured. Again,

the five primary rays may divide or fork repeatedly. Along each radius are usually two or more rows of soft, tube-like processes, terminating in sucking disks; these are the *tube-feet*, which constitute the chief organ of locomotion in starfishes. However, these organs may be completely modified into feelers or respiratory organs in forms that do not crawl about. The tube-feet are connected with the *water-vascular* or *ambulacral system*, a system of tubes peculiar to this phylum, consisting of a circular canal extending around the inner side of the centrally situated mouth, from which branch five canals that run along the center of the arms or radii, these five giving off, in turn, numerous lateral branches which connect with the tube-feet. The sea water has access to this system of canals on the dorsal or upper side of the starfish through a large, porous, sieve-like plate called the *madreporic plate*, and the animals can force the water into the tube-feet and so elongate them into action. Coming in contact with some foreign object, the feet attach themselves by their sucker-like ends and then, by contraction, slowly pull the animal along.

Divisions of Echinodermata. — The Echinodermata are divided into two main classes on the basis of their leading a free or sedentary life. The free forms having fossil representation are the starfishes (including the brittle stars) and the echinids. The sedentary or attached, stalked kinds are the crinids and blastids, nearly all of which are characterized by having a more or less long jointed stalk by which they are, as a rule, fixed to the ground. In the free forms, the mouth is on the under or ventral side, and it is on this side that they crawl about in search of food. The stalked forms, however, are turned over and have the mouth and the ventral surface upward, while from the center of the back or dorsal side originates the stalk, which is usually fastened to the sea bottom. All of the forms that are attached or sessile feed on microscopic food taken out of the circulating sea water. Most of the Echinodermata have the power to reproduce parts bitten off by predatory animals, and a starfish may be torn into several pieces and each piece, under favorable conditions, will regrow the lost parts, because an arm retaining a part of the disk has all the essential organs of an entire starfish.

Free Echinodermata or Asterozoa

Starfishes or Stelleroidea. — The great majority of these animals have a more or less large disc from which radiate at least five arms. The latter may be long and slender or indistinct be-

cause of the enlarged interradial areas. In the latter case, the dorsal side appears as if only the disc were present, but if viewed from the ventral side the five radii, or ambulacral furrows, are seen extending from the central mouth to the tips of the arms. The skeleton buried in the skin is more or less of a mesh of spines, except along the ambulacral furrows, where it consists of distinct and closely adjoining plates perforated by the tube-feet. Because of this loose nature of the skeleton, the parts are easily separated when the animal is dead and for this reason are rarely preserved in their entirety.

Starfishes appeared in the Ordovician, but entire specimens are among the rarest of fossils in Paleozoic rocks (see Fig. 419, an exception to the rule). In the Mesozoic, whole ones are met with more often, but at no time are they of significance in Historical Geology. As limestone makers their dismembered skeletons are of more importance.

Brittle stars (or Ophiuroidea) occur as fossils oftener than the true starfishes but their geologic significance is also small.

Echinids or Echinoidea. — These are the sea-urchins, sand-dollars, and heart-urchins, and, as a rule, are extremely spiny, many

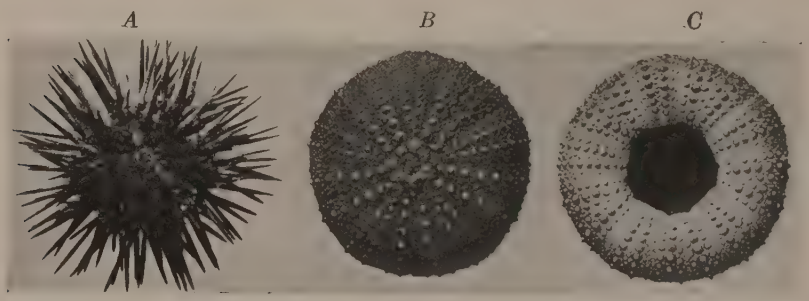


Fig. 392. — Skeletons of two kinds of living sea-urchins (Regularia). *A*, purple sea-urchin (*Arbacia punctulata*), with all its spines, from dorsal side. × ½. *B*, *C*, common sea-urchin (*Strongylocentrotus dröbachiensis*) stripped of its spines to show corona from dorsal and ventral (mouth) sides. × ½. After Coe, Connecticut Geol. Surv.

of the spines being movable on ball-and-socket joints. In general form, the echinids are dome-shaped, the wall of the dome being made up in living forms of twenty columns of closely adjoining plates arranged in pairs (see Fig. 392 *B* and *C*). Five pairs of these are the *ambulacral columns* which are perforated by tube-feet, and alternate with five other pairs which are not perforated, the *interambulacral columns*. The mouth is on the lower or flatter side and is often provided with a powerful jaw of very complicated structure, first described by Aristotle and compared by him

to a Greek lantern, hence it is now referred to as "Aristotle's lantern." At the top of the dome or corona is the anal opening, around which are arranged ten plates in one or two circles. The five large plates of the inner ring are called the *genitals* because each is pierced by an opening, the terminus of the genital organs. The five smaller plates of the outer ring, situated at the termini of the five pairs of ambulacral columns, are known as the *oculars* because in them are located the so-called eyes (see Fig. 394 *B*, but here the plates are arranged in a single ring).

The echinids just described are called *regular echinids* because they are the normally constructed forms, but in the seas of to-day there are many others whose structure is less normal and which

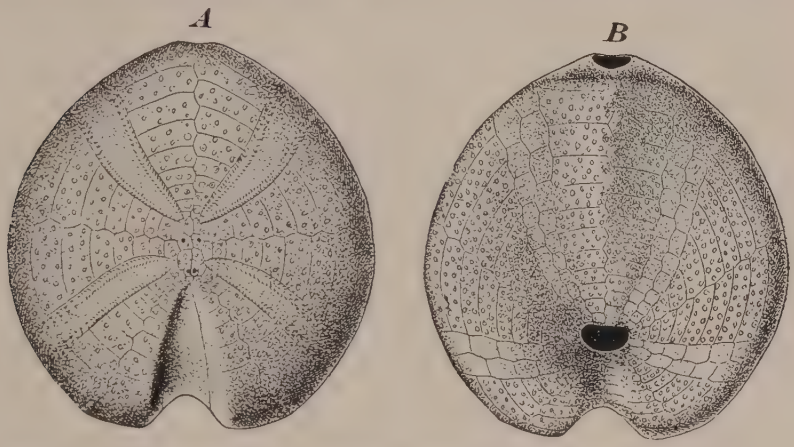


Fig. 393. — Fossil heart-urchins (*Cardiaster cinctus*) from the Cretaceous of New Jersey (Irregularia). *A*, from dorsal, and *B*, from ventral side. After W. B. Clark, U. S. Geol. Surv.

are known as *irregular echinids*. Their irregularity consists in that the anal aperture is not at the top of the dome but on the posterior ventral surface (see Fig. 393). Further, they are not circular in outline but are somewhat elongate, often lobate and heart-shaped, and hence are called heart-urchins. The sand-dollars are also of the irregular type. The spines in these forms are very short and slender and usually there is no lantern-like jaw.

The echinids described above are practically unknown in the Paleozoic rocks, but, appearing in the earliest Mesozoic, become more and more varied and are of much importance in Historical Geology. This is particularly true for Europe, where the Mesozoic strata are at times crowded with them, but in America they are always rare except in the Comanchian beds of Alabama, Texas,

and Mexico. The regular echinids were not rare in the Triassic, but the irregular forms did not arise until late Jurassic time and were not common until the Comanchian. Both of these stocks are common in the present seas, with about 500 species. About 2500 fossil forms are known.

Paleozoic Echinids. — The Paleozoic echinids differ from the later ones in having as many as seventy-five columns of plates in the dome (corona) (see Fig. 394). Here the ambulacral areas have from two to twelve rows and the interambulacrals from three to eleven. Further, the plates usually overlap like the shingles on a roof. These forms appeared in the Devonian but were not common until the Mississippian, when the melon echinids (*Melonechinus*) were characteristic. In the Pennsylvanian and Permian

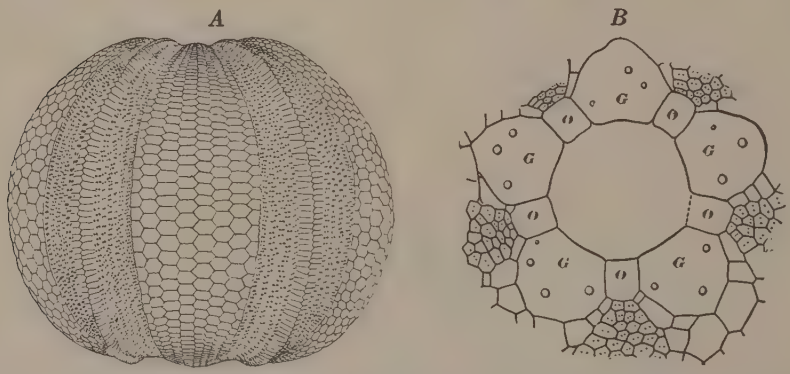


Fig. 394. — Paleozoic echinid (*Melonechinus multiporus*) from St. Louis, Missouri. Note the many columns of ambulacral (perforate) and interambulacral (imperforate) plates. *A*, from the side. After Keyes. *B*, apical disk showing genital plates each with three pores (*G*), and ocular pieces (*O*). About nat. size. After Jackson.

occurred the forerunners of the regular echinids in the ancient cidarids (*Archeocidaris*) which had, however, more than twenty columns of plates.

Sedentary Echinodermata or Pelmatozoa

Crinids or Crinoidea (means *lily form*). — The crinids are popularly known as sea-lilies or stone-lilies, names that give very erroneous suggestions as to their nature, since they are animals and not plants. A better name is *feather-stars*. They are Echinodermata which are usually gregarious in habit and fixed to the sea bottom by a more or less long stalk; there are, however, also many free forms that crawl or swim around. They consist of three main

parts: (1) the *calyx* or body proper, (2) the *arms*, and (3) the *stalk*. The calyx and arms together are referred to as the *crown* (see Fig. 395, also Pl. 9, Fig. 4, and Pl. 6, Fig. 5). The calyx may be large or small and is made up of a variable number of closely adjoining plates, which are arranged in a very definite manner in the different forms, and the crinids are classified according to their arrangement — a scheme too complicated to describe here. From the upper part of the calyx arise the arms or radii, hardly ever less than five in number, and these may fork once or many times according to a regular or irregular plan, but most often in multiples of five. The arms are made up of single or double columns of plates and may have a regular series of small armlets arising from their inner edges and known as *pinnulæ*, suggesting the barbs on a feather (hence the name *feather-stars*). The ambulacra are situated along the inner sides of the arms and pinnulæ where the microscopic food is captured and conveyed to the mouth at the top of or within the calyx. The *anal aperture* is also on the upper or ventral surface of the calyx but is always more or less eccentrically situated and often drawn out into a long anal tube (Fig. 395 *A*). The stalk consists of many superimposed, disc-like, perforated pieces called columnals. It is usually short, from 6 to 18 inches in length, but in one Jurassic form attains 50 feet.

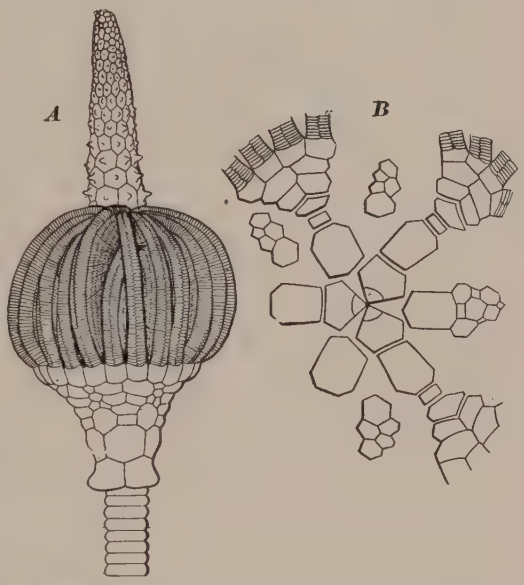


Fig. 395. — A box crinid (*Batocrinus pyriformis*) from the Mississippian of Iowa. *A*, stalk, calyx, arms, and anal tube, from the side. *B*, plates of calyx spread out to show shape and arrangement. After Keyes, Geol. Surv., Missouri.

Ancient Crinids. — In the Paleozoic, crinids at times were very common, especially the forms known as the box crinids (Camerata). In these, the calyx was large and box-like, with thick plates that usually held together tightly (see Pl. 19, Figs. 10, 11). Their

remains are sometimes so common as to make thick crinid limestones, this being especially true in the Mississippian formations.

Crinids appeared early in the Ordovician but are not common fossils until the Silurian, when they are plentiful, and remain so until near the close of the Paleozoic era. However, good crowns are rarities, although the fact that the crinids swarmed in the Paleozoic seas is attested by the many beds of crinid limestones. The cause of this lack of good preservation is that the loose skeletal pieces lay embedded in the skin, which readily decomposed on the death of the animals, and, as their habitat was in shallow seas, the moving waters washed the plates apart.

The crinids of the Mesozoic are less abundant and in American deposits are indeed very rare. They are very different from those of earlier times and more like those inhabiting deep water to-day. In Europe, crinids are common in the Triassic and Jurassic.

Blastids or Blastoidea (means *germ* or *bud*) are small, stalked, extinct Echinodermata that arose in early Ordovician time. In a broad way, these fossils resemble nuts and because of this the people in the southern states, where they are common, often call them "fossil hickory nuts" (*Pentremites*). We may say they are like crinids in their general construction, but they differ at once in that blastids have no arms, only delicate armlets called brachioles. These are situated at the sides of the five large and conspicuous ambulacral areas seen on the sides of the calyxes, areas which are practically never seen in crinids. In blastids the calyx is usually made up of thirteen plates (see Pl. 16, Figs. 1–3, Pl. 20, Figs. 6, 7).

Blastids appeared in the Ordovician, and, while often seen in Devonian strata, were not common in America until Mississippian time, when the seas abounded in them. They are guide fossils of this time, but died out early in the Pennsylvanian.

CHAPTER XXXVI

SILURIAN TIME AND THE FIRST AIR-BREATHING ANIMALS

Origin of the Term Silurian. — The term Silurian was proposed by the great English geologist, Murchison, in 1835, for a series of sedimentary and interbedded volcanic rocks which the older geologists called "Transition Rocks" or "Graywacke." These rocks occur in western England and eastern and southeastern Wales, the country of the ancient Britons known as Silures.

Fig. 396. — Roderick Impey Murchison (1792–1871). Author of Silurian, Devonian and Permian systems.

The original Silurian is now known to be overlain unconformably by fresh-water deposits called the Old Red sandstone, and referred to the Devonian; below, Murchison left his system undelimited and finally claimed all of Sedgwick's Cambrian strata that yielded trilobites and brachiopods. Because of this inclusion there arose between them a long controversy which, so far as terminology is concerned, seems not yet to be settled.

The upper boundary of the original Silurian long remained undefinable because of the absence of marine fossils and the erroneous conclusion that the beds passed gradually into the fresh-water Old Red sandstone. The adjustment was finally made in Germany (Harz region) and Bohemia, and, on the basis of this determination, the upper boundary of the Silurian in America is now placed at the top of a series of beds called the Manlius.

Murchison divided his system into a Lower and an Upper division. The boundary between them was finally established where an angular unconformity separates the Caradoc from the Llandovery groups, as first pointed out by Sedgwick. The controversy for the present is adjusted by calling all of Sedgwick's

Lower Cambrian that is almost unfossiliferous, Cambrian; his Upper Cambrian, to which he really wished to have the term restricted, and which Murchison called Lower Silurian, is now named Ordovician; while to the latter's Upper Silurian is now applied the period name Silurian.

American Silurian

Almost everywhere in North America the strata of the Silurian system are easily separated from the Ordovician below by a more or less long " break " or interval. Throughout the New England States and the Maritime Provinces of eastern Canada the two systems are separated by an unconformity marking the movement

Fig. 397. — Ordovician-Silurian unconformity at Otisville, N. Y. Above are conglomeritic sandstones (Shawangunk), resting on the peneplained surface of Ordovician shales (Martinsburg). Unconformity due to the Taconic Disturbance.

of the Taconic Disturbance (see Fig. 397), but in the great interior region of the continent the separation, as a rule, can only be made on the basis of the entombed fossils (see Fig. 398). On Anticosti Island in the Gulf of St. Lawrence may be studied the most complete American section. Even here, however, the two periods are seemingly separated by a break or interval.

The American Silurian is divided as follows:

Upper Silurian or Cayugan	Monroe group. Salina group	Manlius the youngest formation
Middle Silurian or Niagaran	Guelph dolomite Lockport dolomite Rochester shale Clinton formation	Louisville limestone
Lower Silurian or Oswegan	Medina, Cataract, and Brassfield formations Becsie limestone	

Advance and Retreat of the Seas in America. — Unlike those of the Ordovician, the Silurian deposits of America record but a single oceanic spreading and a single continental emergence. During Lower Silurian time, the small seas were at first situated on the

Fig. 398. — Ordovician-Silurian disconformable contact, Niagara River gorge, N. Y. Note even contact of white Silurian sandstone (Whirlpool-Cataract) on brick-red, sandy, Ordovician shales (Queenston).

northeastern part of the continent and later in the Appalachian trough, as shown on the paleogeographic maps. In Middle Silurian time, the marine waters flooded the continent widely, especially in the northern half, and attained the maximum of their spread toward the close of this time (Louisville), when it is thought that from 35 to 40 per cent of North America was under water. The submergence retreated shortly afterward, the Central Interior sea withdrawing first, and later the Arctic waters. During the Upper

Silurian epoch a very shallow sea remained in the northern Appalachian and Central Interior areas, depositing along its northern shores considerable salt and gypsum. It is probable that toward the close of the Silurian the entire continent was emergent, except a small part of the Appalachian trough in Maryland and Pennsylvania and the outer St. Lawrence trough (Gaspé).

Cincinnati Uplift. — This low arch, described in Chapter XXXIV, was not a marked topographic feature in the seas of Ordovician time (see page 636), but throughout the Silurian distinct marine basins lay on either side of it. Floods from the Gulf of Mexico extended northward and covered the areas to the east and west of the arch, but along the western side the waters were most persistent during the Niagaran epoch. The Ozark uplift was also a striking feature of these seas, confining the southern floods to its eastern and southern sides in eastern Missouri, Arkansas, and central Oklahoma.

If the Middle Silurian flood at its height be compared with the greatest submergences of the Cincinnatian and Champlainian epochs of the Ordovician, it is seen that great changes had taken place, for there was much more emerged land in the western part of the United States during Silurian time than before. Great areas were upwarped and persisted there as lands even long after the Devonian.

Character and Thickness of Silurian Rocks. — *Eastern United States.* — In the Appalachian trough the sedimentaries are coarse-grained throughout until near the close of the Silurian, when much compact or dense cement rock or water limestone was deposited in very shallow seas, as is indicated by its very decidedly sun-cracked nature. These coarse-grained rocks are the results of rapid erosion from the high lands of Acadia following the Taconic Disturbance. In east-central Pennsylvania the thickest accumulations occur, with a maximum of 6490 feet. Of this mass the lower 4490 feet are almost devoid of limestones, the strata being cross-bedded sandstones, sandy shales, shales with a little sandy limestone, and, toward the top of the series, local beds of valuable fossil iron-ore. The upper 2000 feet of Upper Silurian age consist of shales gradually becoming more and more calcareous toward the top, which, in New York, Ohio, and western Ontario, bear valuable deposits of rock salt and gypsum. This great mass of Silurian material thins rapidly to the south and north and probably also to the west under the coal fields of the Allegheny region. In the Niagara Falls area of New York there are about 180 feet of shale, sand-

stone, and dolomite that thicken rapidly to the south under the cover of the younger strata. At the Virginia-Tennessee line there are not more than 400 feet of basal sandstone (Clinch) followed by 325 feet of shales and sandstones (Dyestone) of Middle Silurian time. South of Tennessee these beds again thicken, there being in the Appalachian trough of northwestern Georgia 1600 feet of Middle Silurian strata which thin rapidly to the west end of the state, where 180 feet are present (see Pl. 10).

Acadia. — In eastern Acadia the Silurian is widely spread and often rich in fossils. The thickest section is at Arisaig, Nova Scotia, where there are nearly 4000 feet of shales and sandy limestones. Another fine exposure is that of Anticosti Island in the Gulf of St. Lawrence, with more than 1200 feet of limestones and some shales representing the earliest portion of the American Silurian; the higher beds continuing the section are present farther south along the north shore of the Bay of Chaleur, Quebec. In southern Maine the Silurian is locally very thick, there being in the Penobscot Bay region about 10,000 feet of volcanic tuffs and detrital land sediments. This thickness, however, does not include the volcanics and lava flows, which also have considerable depths.

Silurian Sequence at Niagara Falls. — Between Buffalo, New York, and the region about Niagara Falls may be studied a typical Silurian section and one of the finest exposures in America for fossils of this time. The gorge between the Falls and Lewiston has the lowest strata reposing on the Ordovician, while the younger deposits appear in sequence toward Buffalo, where some of the Middle Devonian is also to be seen in the Bennett quarries. The diagram, Fig. 399, shows the sequence of the beds and Fig. 400 pictures them as they appear in the walls of the gorge of Niagara River. All of the strata have a gentle dip southward.

Interior of North America. — Here the Silurian seas had clear waters, and their deposits were almost entirely calcareous. Almost all of them were of Middle Silurian time. The strata were widely distributed in two epeiric seas, one being the smaller southern Central Interior sea and the other the far larger sea of the Arctic region. Nowhere are these deposits thick when compared with those of the Appalachian trough, and, unlike the latter, they are largely limestones, dolomites, and calcareous shales, with almost no sands. In no place does the thickness exceed 1000 feet and in general it is usually considerably under 500 feet.

Rocky Mountains. — The Silurian of western North America is not yet well known and appears to be poorly developed through-

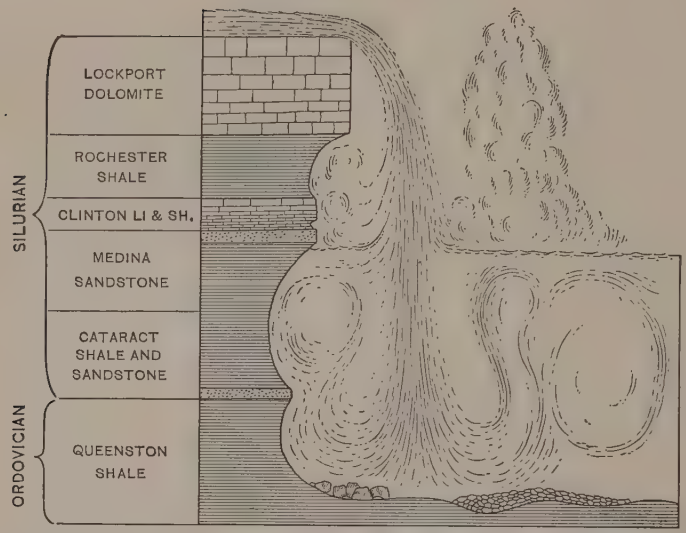


Fig. 399. — Sectional diagram through Horseshoe Falls, Niagara River, showing sequence of formations and depth of water below falls. Height of falls, 158 feet; depth of water, 150–200 feet. Modified from G. K. Gilbert.

Fig. 400. — General view of New York side of Niagara River gorge. Clinton limestone at track level, the long slope is Rochester shale, and the vertical upper walls are Lockport dolomite.

out the United States. In the Cordilleran sea of Canada, however, there was another deep trough, for near the International Boundary (Bow Pass) there are 1300 feet of dolomites and quartzites. This trough deepened northward, since in the western Mackenzie valley (Gravel River) there are 2000 feet of dolomites, and in Alaska at the Lower Ramparts of the Porcupine River there are 2500 feet of dolomites with some black shale. In southern Alaska in the region of Kuiu Island there are 2000 feet of limestone (see Pl. 10).

In the southern portion of the Cordilleran sea little is known of the Silurian deposits, but such are seen to occur in Nevada and in the Utah area of the Great Basin, where 200 to 300 feet of magnesian limestones have unmistakable Silurian fossils. In the Franklin Range of western Texas there is another Silurian area of a distinct sea, also apparently of Pacific origin; here there are 1000 feet of Middle Silurian limestones.

Life of the Silurian

Marine Provinces. — On the basis of their entombed faunas the American Silurian deposits are geographically divisible into three provinces. These are (1) Atlantic, (2) Arctic, and (3) Cordilleran (see Pl. 10). The best known of these, with the longest and least broken record, is the Atlantic province, embracing the Silurian deposits of the Acadian area and the Appalachian trough. The Arctic province is only of Middle Silurian time, includes much of the northern interior parts of the continent south almost to the Ohio River, and has decided faunal connections with the Baltic area of northern Europe, the intercommunication being by way of northern Greenland. In the Cordilleran sea the Silurian faunas are not well known, but appear to be of Pacific origin.

Marine Invertebrates. — As is usual in marine sediments, practically nothing of the soft sea plants is preserved, although the Silurian life record is almost entirely that of the shallow seas wherein algæ abound. The invertebrates still dominated the seas because the fishes were as yet not at all prominent, though appearing more abundantly in the late Silurian seas of Europe. The common Silurian fossils are mainly corals, crinids, bryozoans, brachiopods, and trilobites (see Pl. 9). Of nautilids there are less than a hundred kinds known in America, but in Bohemia, where the sea had Mediterranean connections, the warmer waters swarmed with them, Barrande having described from this small area 1150 species. The Silurian was, however, the time of greatest nautilid development

and since then there has been a steady decrease in number of species. True graptolites were still common in the European seas, but in America they are not often found as fossils, although the dendroid forms are, in places, common, as at Hamilton, Ontario, where 52 species occur.

Of crinids there are nearly 400 kinds known in the American Silurian, a far better development than in the Ordovician; many of these beautiful fossils have thick calcareous skeletons and are therefore spoken of as box crinids (Camerata, described on page 657). These crinids must have existed in great numbers, for their skeletons often make up thick limestones. The bryozoans were

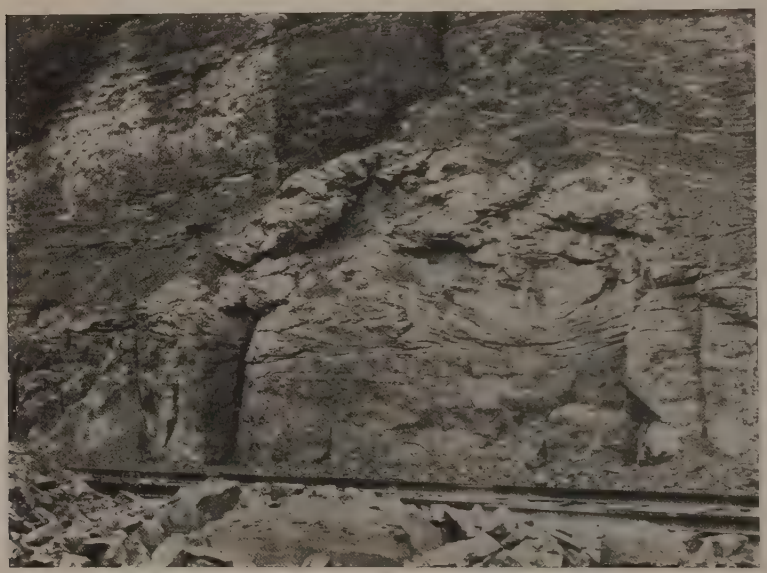


Fig. 401. — Small reef made by bryozoans, Niagara River gorge, N. Y. The reef (15 feet long) rests on Clinton limestone and projects into Rochester shale.

also common, about 200 forms being known, but while they made small reefs in the Clinton, they were not so prolific as in the Ordovician (see Fig. 401).

Of brachiopods there are about 350 kinds described from the Silurian of America (see Pl. 9). Although their general development was still much like those of the Ordovician, they were, on the average, larger and more robust. There was also at this time a distinct change in the introduction of many forms that have internal spiralia or calcareous supports for the arms (page 611), and in the abundance of rhynchonellids and pentamerids.

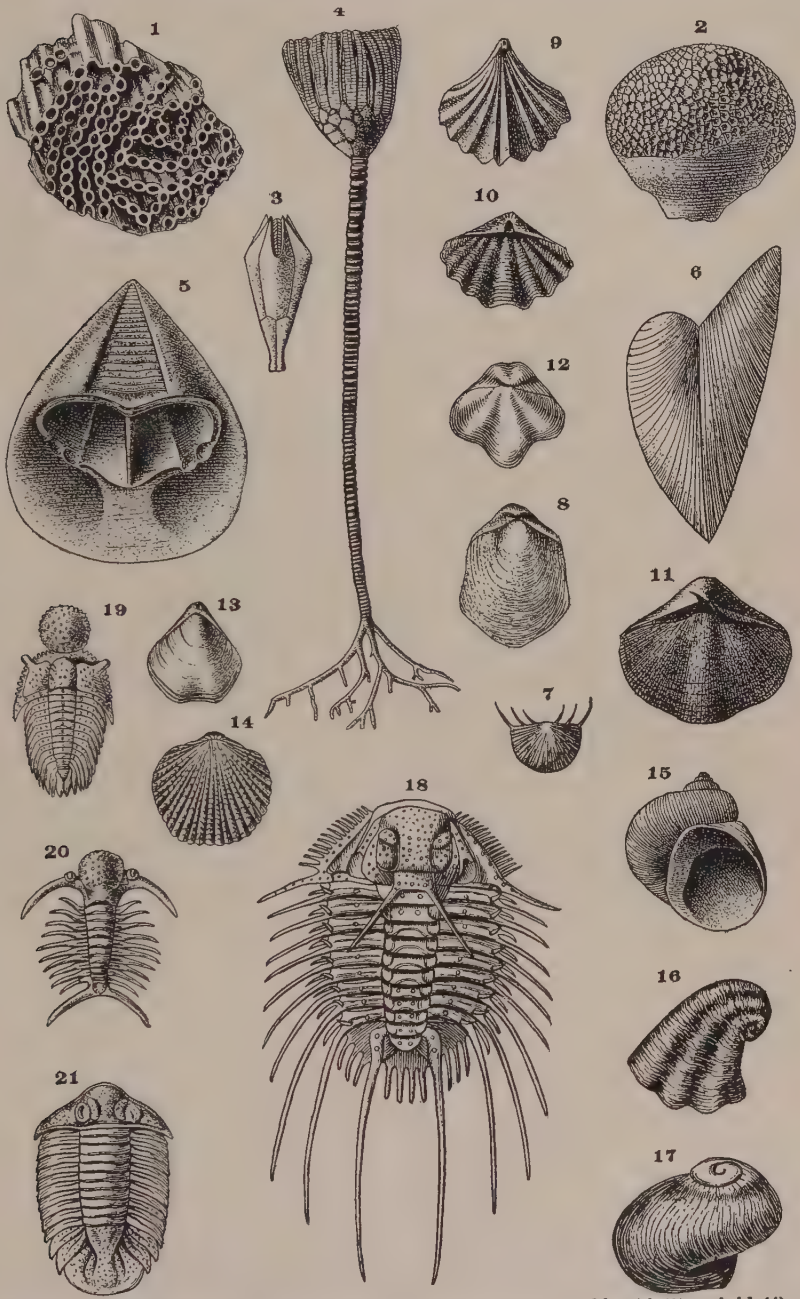


Plate 9. — Silurian corals (1, chain coral; 2, honeycomb coral), blastid (3), crinid (4), brachiopods (5–14), gastropods (15–17), and trilobites (18–21).
See Appendix B.

Of trilobites there were still at least 105 American species, many of which were bizarre looking animals with many spines on the head and tail (see Pl. 9). Spinosity is often interpreted as indicating an ebbing of the vital force among the trilobites, but in some forms it may have been a protective device against the carnivorous fishes then coming into being.

Throughout the Silurian, but more particularly in the Upper Silurian, the "sea scorpions" or eurypterids were common (see Pl. 12). They usually occur in brackish-water deposits that otherwise are devoid of fossils, and very similar kinds are found in

Fig. 402. — Silurian coral reef limestone, near Wisby, Gotland, Sweden. The coral reef lies above the regularly bedded limestone.

both eastern America and western Europe. The largest American species is found in New York (*Pterygotus buffaloensis*), where Clarke and Ruedemann have determined for it a length of nearly 9 feet. The eurypterids are particularly interesting in this connection, not only because they are so characteristic of late Silurian time, but also because out of them arose the air-breathing scorpions.

Coral Reefs. — Corals were not common until the Middle Silurian, and then at many places in America they made reef limestones (see Figs. 402 and 145). The best examples of these are seen in Wisconsin, Iowa, and the Manitoulin Islands, and to a more limited extent

at Louisville, Kentucky. All of these corals are of the kinds known as Tabulata and Tetracoralla, described in the previous chapter.

Associated with the coral reefs, more especially toward the close of the Middle Silurian (Guelph), are seen many thick-shelled animals, most of which are gastropods. Fifty species of these have been described from a limited area (Ontario). Similar associations are seen on the present living reefs, where the molluscs form thick shells, not only because they are necessary against the crushing power of the active waves, but also because there is much lime in the warm sea-water which can be easily extracted.

Cosmopolitan Character of Middle Silurian Life. — The known marine life of Lower Silurian time is scanty, but that which can be found indicates that each area had its own peculiar assemblage. The same is also true of the earliest Middle Silurian faunas, but it is not so marked as in the earlier time. Finally, when the inundation of the continent was greatest, in Middle Silurian (Louisville) time (Pl. 10), the faunas of all the provinces took on a more cosmopolitan appearance and had the greatest number of species in common. At this time there were at least thirty forms in common between northern Europe and America, this similarity being greatest in the Arctic province, a sea in open connection with Europe by way of northern Greenland.

First Land Plants. — The known land plants of Silurian time are as yet exceedingly few, and the specimens are rather indistinct. For these reasons the discussion of the nature of the first land flora is deferred to a later chapter.

First Land Animals. — *Fishes* undoubtedly lived in the fresh waters throughout this period, but almost nothing is known of them until late in Silurian time, when their skeletons are met with in Europe. As they are so much like those of the Devonian, a description of them is postponed until a later chapter.

The *scorpions* of the Silurian are the oldest known air-breathing animals (Fig. 403). They probably had their origin in the eurypterids of the sea, seemingly as early as the Ordovician. The largest one known was 2.5 inches long, and in general structure they were very much like the living scorpions, which live entirely on land. The question therefore arises: Were the adult Silurian scorpions wholly adapted to the dry land, or did they live along the seashore between the tides? Their remains are rarely found in marine deposits, but usually in those of brackish water, and associated with the eurypterids, which would seem to indicate a littoral habitat. Scorpions are carnivorous animals, and the living forms feed on

insects, spiders, and other small forms, killing the prey with their poisonous tail sting. We may assume that the Silurian species lived as do those of the present, and, as the latter are wholly terrestrial, the further question suggests itself: On what could the Silurian forms have fed, since no insects, spiders, or even land snails

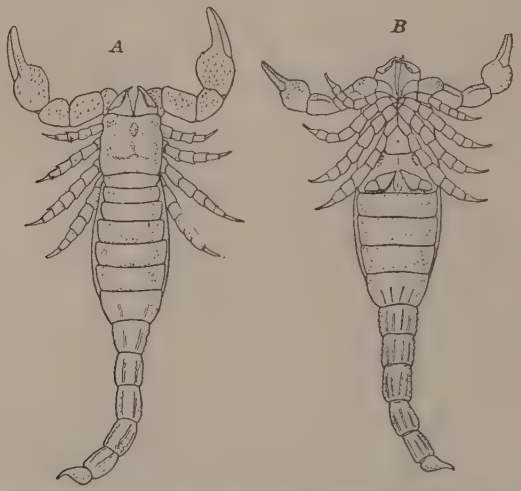


Fig. 403. — Two species of Silurian scorpions, restored. *A*, dorsal side of a Swedish form (*Palæophonus nuncius*). *B*, an English species (*P. hunteri*) from the ventral side. After Pocock.

are known at this time, or for that matter previous to the Carboniferous? As spiders are closely related to scorpions, and as species of the former are known along most sea-coasts, inhabiting the beach between high and low tide, it seems, therefore, a safe inference that the Silurian scorpions also fed and lived, when adult, above the strand-line, though, like frogs, they may have lived in the water during their period of infancy, and that they ate small invertebrates, among them trilobites and small crustaceans. Their wanderings over the land began later with gradual adaptations away from the life of the shores, but this migration could have taken place only when the land had other animals for them to feed upon.

Silurian Climate

As the Silurian seas abounded in varied life and as the deposits in the main were limestones and dolomites even as far north as the Arctic regions, it is safe to infer that these waters were warm. Additional confirmation is had in the fact that the life of the

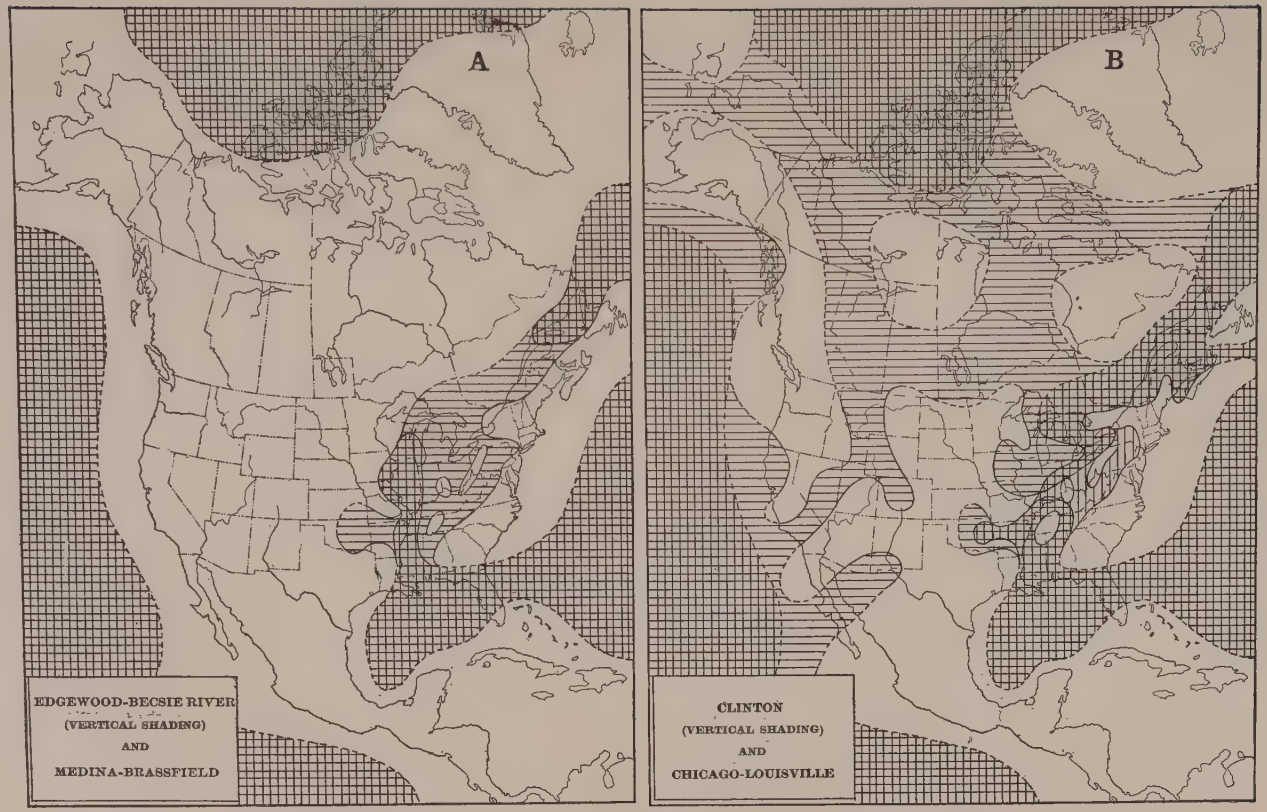


Plate 10. — Lower and Middle Silurian paleogeography.

American Arctic deposits is very much like that of northern Europe and of the United States, while the reef-building corals are practically everywhere the same. The chain coral (*Halysites*, Pl. 9, Fig. 1) and the honeycomb coral (*Favosites*, Fig. 2) are very similar in all the areas, and are found even above 81° north latitude at Polaris Bay. Further, extensive salt-depositing seas existed in eastern North America between 40° and 45° north latitude, indicating an arid or dry climate on the land, though it is not necessary, because of this evidence, to assume that the temperature was hot. We may therefore conclude, on the basis of the character of the deposits and of the life, that the climate of Silurian time, in the northern hemisphere at least, was temperate to warm.

Caledonian Disturbance of Western Europe

An extensive ancient land had long existed immediately to the northwest of Ireland and Scotland, and its rivers brought down into the sea area, now Wales and southern Scotland, 12,000 feet of Cambrian and at least 10,000 feet of coarse Ordovician deposits. During the earlier half of Ordovician time a line of volcanic islands stretched across Ireland and the north of England in a southwest and northeast direction, and there is in the Cambrian area at Keswick at least one pile of volcanic ejected materials fully 12,000 feet thick. The deformation toward the close of the Ordovician, as the result of this loading, was, however, not wide-spread, for Geikie states that in Wales these strata were ridged up into a series of islands, around the margin of which the conglomerates at the base of the Upper Silurian series began to be laid down. Of Silurian deposits there follow 6000 and in places even 15,000 feet, which locally lie discordantly upon the Ordovician, the deposition going on until well toward the end of the former period, when there occurred the culmination in the making of the Caledonian mountains, ranges that extended from Ireland and Scotland as far as Spitzbergen. Other ranges also came into being in France and Belgium. That these movements took place late in the Silurian is shown by the fact that the Devonian Old Red sandstones were not involved in the foldings and thrustings, while the youngest strata in the folds are of late Silurian time.

With the Caledonian Disturbance is probably to be connected the withdrawal of the seas in North America and in northern Europe, the emergent period lasting through all of late Silurian and early Devonian time.

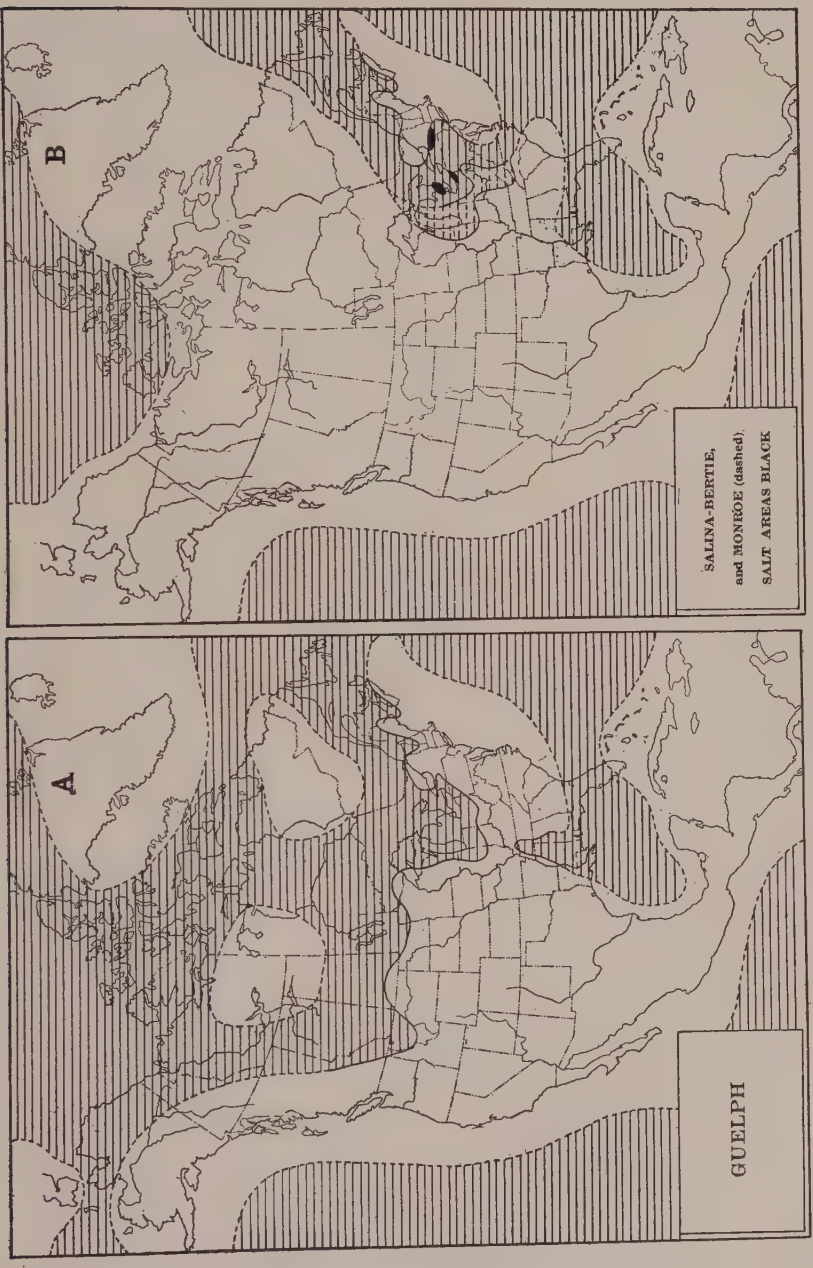


Plate 11. — Middle and Upper Silurian paleogeography.

This crustal movement, resulting in the Caledonides, as Suess terms these mountains, may be regarded as the first important stage in the building of the British Isles, and the Caledonian range must have been much grander and loftier than the Alps (Jukes-Brown). The significance of the movement is best seen, however, in Norway and Sweden, where the pre-Devonian strata have been overturned and pushed horizontally eastward at least 86 miles. The thickness of the moved mass is usually less than a mile, but originally it must have been much greater. On the other hand, it appears almost certain that the Scandinavian countries have for a long time lain at a low level in respect to that of the sea, for great parts of Norway and Sweden were again invaded by it in late Cretaceous time. The present mountainous character of Norway is undoubtedly due to deformation in late Tertiary time, an elevation that must have been a few thousand feet higher then than now, as proved by the deeply submerged marginal valleys, the beautiful fiords of Norway.

Rock Salt

Occurrence. — Rock salt and gypsum may have accumulated in the sedimentary strata at any time and place when the necessary physical conditions, discussed on pages 76 to 79, were present. In America extensive salt-depositing basins came into existence toward the close of the Silurian (Salina formation) in New York, Ohio, and Ontario (Pl. 11, Fig. B). The salt brines of western West Virginia, on the other hand, rise from rocks of Upper Devonian age and those of southeastern West Virginia are of early Mississippian time, while in southern Louisiana occurs rock salt of Tertiary age. The most interesting and by far the thickest beds, however, occur in Germany near Berlin (Sperenberg, 3250 feet of marine salt), and at Stassfurt in southern Saxony, where there is an average thickness of 3400 feet of salts. These deposits are of Middle and Upper Permian time. At Stassfurt occur more than thirty saline minerals, and it is estimated that the salts here were accumulated in less than 10,000 years, a calculation based on the many so-called annual layers which are clearly demarcated.

Silurian Salt in New York. — The Salina formation of New York consists mainly of reddish shales with some thin bands of dolomite. Its outcrops extend as a narrow belt across New York State from the Helderberg Mountains westward to Niagara Falls, where the thickness is 380 feet in well borings. From this belt the strata dip southward beneath the younger formations, and 25 miles nearly south of the Batavia outcrops they are 1000 feet beneath the surface, and 1500 feet at a distance of 33 miles. At Syracuse the thickness of the formation is about 600 feet, at Ithaca 1230 feet. Salt springs occur in many parts of New York west of Syracuse and Tully. Rock salt occurs in New York at depths of 800 to 3000 feet or more, over an area measuring 150 miles from east to west, and 60 to 65 miles in width if regarded as extending only to the Pennsylvania boundary. The northern limit of the area is near Morrisville, where 12 feet of salt were found, and near Leroy, 100 miles west of Syracuse,

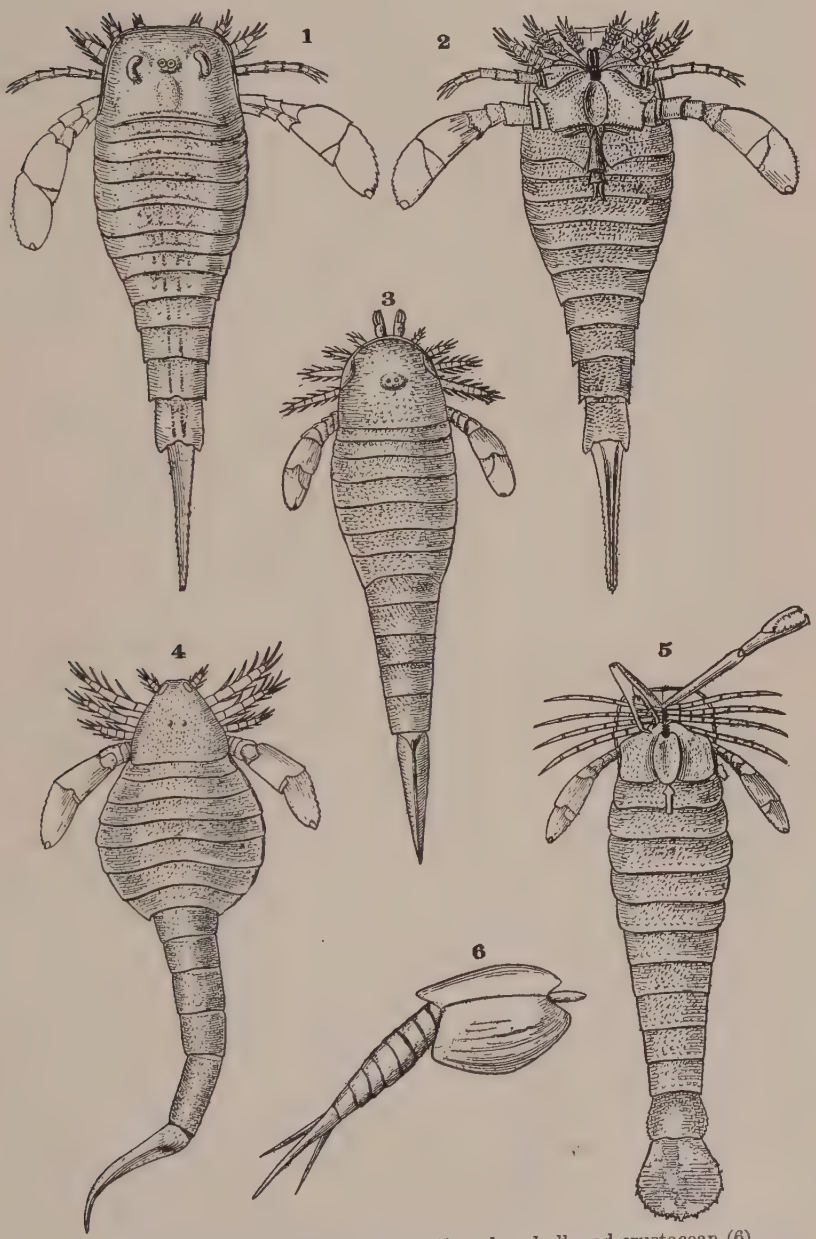


Plate 12. — Silurian eurypterids (1–5) and a phyllopod crustacean (6).
See Appendix B.

where a bed 40 feet thick exists. In Livingston and Wyoming counties the salt beds have an aggregate thickness of 50 to 100 feet, some beds of pure salt being 40 to 80 feet thick. At Ithaca the seven beds of salt have together a thickness of 250 feet and they alternate with shale between depths of 1900 and 3130 feet. (Dana.) For distribution see map, Pl. 11, Fig. B.

Theory of Salt Formation. — Beds of rock salt, in a section, may be separated from one another by clay, limestone, or dolomite, or there may be a single bed of very variable thickness and made up of many kinds of salts.

Ocean water contains, on the average, about 3.5 per cent of solid matter in solution, most of which is sodium chloride or rock salt (78 per cent of the sea salts), and it contains also calcium sulphate or gypsum (about 3.5 per cent) (see page 83). The two compounds are commonly associated with each other, but not invariably, for gypsum is sometimes derived from other sources, and rock salt may be dissolved and washed away from a given locality, leaving the gypsum. Still, concentration of the oceanic salt water is the principal source of these deposits. In general, the following is the order of deposition: (1) precipitates of lime carbonate and some hydrous iron oxide; (2) most of the gypsum, which precipitates when 37 per cent of the sea water is evaporated; (3) mixtures of gypsum and common salt; (4) pure sodium chloride, when 93 per cent of the original water is gone; (5) in exceptional conditions, mixtures of sodium chloride with salts containing magnesium, potash, bromine, and iodine. This order, however, is subject to seasonal alterations, variations in temperature, and other conditions, so that alternations of gypsum, salt, and clay are exceedingly common in saline deposits.

It is probable that all of the more extensive accumulations of sodium chloride and calcium sulphate are connected with marine sedimentation, under dry, warm, or cool to even cold climates, in very shallow seas or bays more or less shut off from the oceans by land bars or barriers and previously described as detached salt lakes (page 79). The essential conditions are (1) a dry climate constantly taking away by evaporation some of the water in (2) nearly land-locked seas, and (3) the supplying of the loss at frequent intervals (high tides) from the oceans. These waters must, therefore, be practically free of circulation, at least with no greater flow than that produced by the tides at the heads of bays. The Salina sea must have been an extensive shallow basin with openings out into the Atlantic Ocean.

Absence of Fossils in Salt Beds. — In basins supersaturated with salts one naturally would not expect much life, and when the

saturation is marked (15 to 22 per cent) they are dead seas. Even where the saturation is but a little above that of the ocean, animal life becomes scarcer and the molluscs make thicker and rougher shells. The Salina and Permian seas in the places of salt accumulation were lifeless.

Other Economic Products

Clinton Fossiliferous Iron-ore. — In the Clinton formation of the Appalachian trough from New York to Alabama, there occur in many regions one or more beds, varying from a few inches to 10 and even 20 feet in thickness, of regularly stratified, argillaceous, red iron-ore or hematite (Fe_2O_3). They were formerly mined throughout the Appalachian Mountains, but now are worked extensively only in the Birmingham region (Red Mountain) of Alabama. The ore is usually more or less cross-bedded, fossiliferous, and made up of clay, oolites, and the fragments of invertebrate animals, the calcium carbonate of which is now more or less replaced by ferric oxide; the deposits are, therefore, often called " red fossil ore." The beds were evidently made in storm-beaten shallow seas where trituration or breakage of the shells was marked, with a loss of the carbonic acid. Frequently, the grain of the ore is similar to that of oolitic limestone or the particles are flattened like flaxseed, and accordingly the ores are also spoken of as oolitic and flaxseed iron ores. In Tennessee, they are known as the Dyestone ores.

Clinton Oil and Gas. — In recent years, the Clinton sandstones of central Ohio and eastern Kentucky have yielded locally considerable oil and some gas.

Geological Map. — The surface exposures of Silurian strata are shown on the Geological Map of North America at the end of this book.

CHAPTER XXXVII

FISHES AND THE ANCESTORS OF VERTEBRATES

The word fish, from the Latin *piscis*, is a very old one and popularly has reference to any animal that spends its entire life in the water. Therefore, the word, as commonly used, covers a variety of unrelated animals, some of which are distinguished by a prefix, as jellyfish, starfish, shellfish. None of these are fishes in the sense in which the term is used by naturalists, whose class name *Pisces* includes only the true fishes, animals with backbones but of great structural diversity and also of great antiquity, whose history may be traced to at least the middle of the Ordovician. The fishes in the strict sense form a class of the subkingdom Vertebrata, with the same rank as the Amphibia (frogs and salamanders), Reptilia (turtles, crocodiles, lizards, snakes), Aves (birds), and Mammalia (dogs, horses, man).

Fishes were the first markedly successful class of vertebrates. With the possession of a vertebral column and a central nervous system, and with their greater alertness, mobility, and fecundity, they have an easy preëminence over their invertebrate inferiors. They are as markedly adapted to the water as the birds are to the air.

Definition of Fishes. — Fishes are vertebrates without a movable neck and with a distinct and hinged *lower jaw*. With few exceptions, they pass their whole life in water. Their body temperature is about that of the medium in which they live, wherefore they are said to be cold-blooded. Because of their water habitat, all fishes have *gills* and *fins* (see Fig. 404). The gills are on each side of the head and consist of delicate, hollow filaments in which the blood circulates, and which are supported by internal gill arches of either cartilage or bone. Water is taken in through the mouth and passed out over these breathing organs, where the blood in the tubes extracts the free oxygen dissolved in it. The external gill openings may remain open and unprotected or may be covered over by a hinged bony cover, the *operculum*. The *mouth* may be on the under side of the head or at its forward end, and is usually provided

with teeth. An *air bladder* is generally present and serves as a hydrostatic organ or float, though in certain forms it acts as a lung and assists the gills in respiration.

The heart, which is two-chambered, contains only venous blood, that is, blood which it is pumping through the veins to the gills to be purified; in the Dipnoi, or lung-fishes, however, it shows signs of becoming three-chambered, and receives pure blood from the lungs as well as impure blood from the body. In all the fishes except the Dipnoi, one chamber of the heart, called the auricle, receives the impure blood from the body, and the other cavity, the ventricle, drives this through a ventral aorta to the gills, whence the purified blood flows to the head, and then, by a dorsal aorta, or artery along the back, is carried to the body.

The skin is either soft and naked, or, more commonly, protected by the development of spines, overlapping scales, or bony plates known as scutes. The principal organ of locomotion is the power-

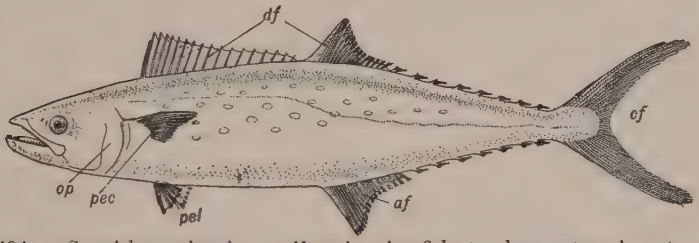


Fig. 404. — Spanish mackerel, a swift-swimming fish, to show external parts. After Goode. *af*, median anal fin; *cf*, caudal or tail fin; *df*, dorsal median fins; *op*, left operculum or movable covering over gills; *pec*, one of the front paired or pectoral fins; *pel*, paired pelvic fins, which may in different fishes be situated anywhere from this position back to a place in front of the anal fin.

ful and very flexible muscular tail. This is assisted by the *paired fins*, of which the forward set, known as the *pectoral limbs*, lie just behind the gills, and the rear pair, or *pelvic limbs*, are placed farther back (see Fig. 404). The paired fins of fishes correspond to the fore and hind limbs of the higher vertebrates. Their skeleton, however, cannot be readily compared with the limb-skeleton of other vertebrates, because it has not the same bones nor the five toes which are, with few exceptions, so regularly present in all higher vertebrates. Fishes also usually possess a variable number of *unpaired median fins* that are used mainly as balancing organs; those on the back are called *dorsal fins*, those on the under side between the anus and tail are known as *anal fins*, and the tail represents a *caudal fin* (see Fig. 404). All the fins are supported by skeletal bars or rays, called fin rays, and are covered by muscles

and skin. The skeleton throughout may be of cartilage, though usually it is more or less bony. The main skeleton consists of the *vertebral column*, made up of joints known as vertebræ, and the complex bones of the head, which serve also as a protective covering for the brain. The bones of the head are of two kinds, dermal or skin bones like the scales, and the actual bones of the brain case. Fishes do not have ears, and therefore there is no ear drum or tympanum (ear cavity) and no tympanic membrane. The *main nerve trunk* lies on the upper or dorsal side of the vertebræ, which extend from the brain case to the tail, and it is more or less protected by a bony arch known as the neural arch. Beneath the vertebral column are situated the digestive and reproductive organs.

Types of Fish Tails. — The tail presents three general types. (1) The vertebral column may be straight at its posterior end, continue in constantly diminishing joints nearly to the end of the animal, and be there surrounded by a symmetrical vertical tail fin. This is the most primitive type, very common among the Devonian fishes, and seen in the baby stages of most living fishes; it is known as the *diphycercal* or symmetrical tail (see Pl. 14, Fig. 4). (2) In others, the vertebral column bends upward toward the dorsal side and terminates with diminishing joints in the upper lobe of the dorsal fin. Hence, this type of tail is rarely symmetric but is commonly unevenly lobed as in the living sharks and in most Paleozoic fishes; it is called the *heterocercal* tail because of the inequality of the lobes (see Pl. 13, Figs. 2 and 4, Pl. 14, Figs. 1, 2). (3) The modern bony fishes also have, as a rule, a symmetric tail, but, while the vertebral column here again bends upward, it ends rather abruptly, and from the terminal joints the fin rays develop in such a way as to form a symmetric tail. This kind of caudal appendage is called *homocercal* (see Fig. 405); while the tail is symmetric it also has two lobes, whereas the diphycercal type has but a single lobe.

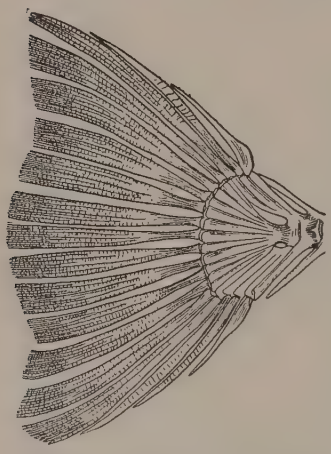


Fig. 405. — Skeleton of the homocercal tail of a flounder.

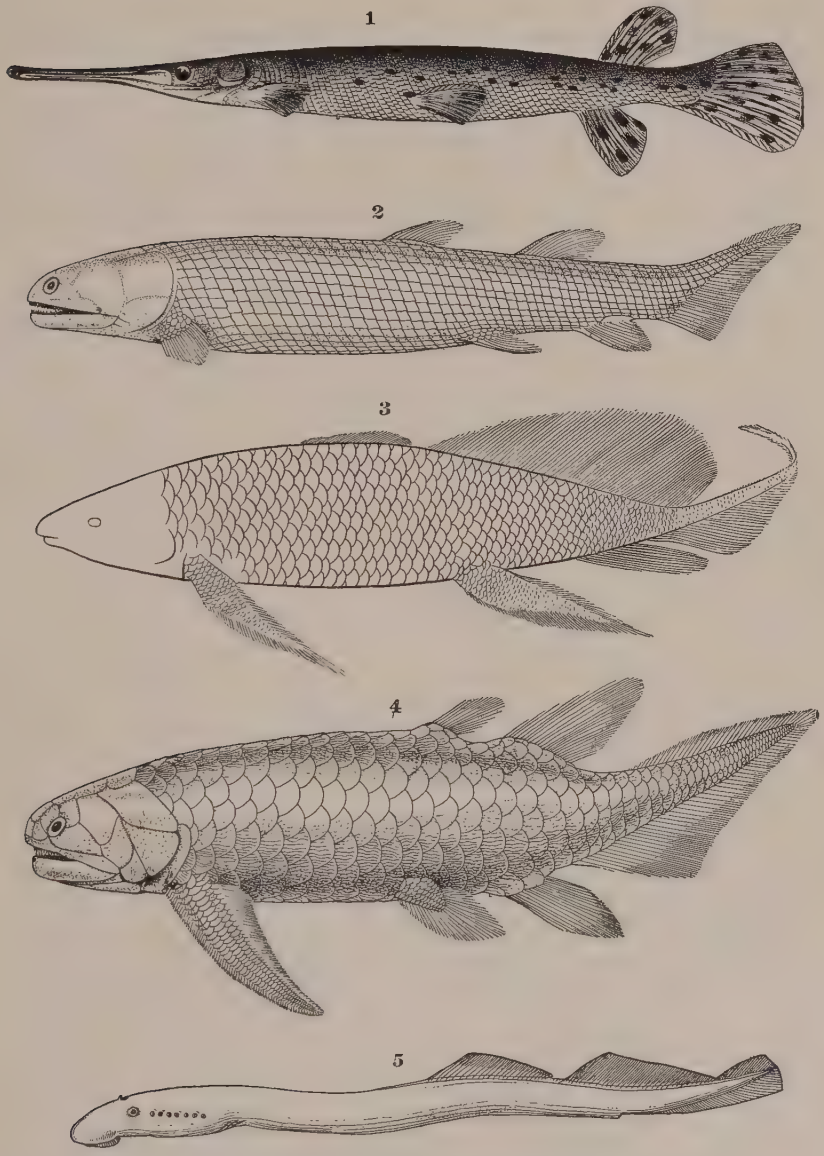


Plate 13. — Living ganoid (gar-pike) (1), fossil ganoids (2–4), and living marine lamprey (5). See Appendix B.

Classification of Fishes. — For present purposes, fishes may be divided as follows:

Class **Pisces** or true fishes.
  Subclass **Elasmobranchii** or cartilaginous fishes.
    Order **Acanthodei** or spinous sharks.
    Order **Selachii** or true sharks and rays.
  Subclass **Ostracodermi** or bony-skinned fishes.
  Subclass **Dipnoi** or true lung-fishes.
  Subclass **Arthrodira** or armored fishes.
  Subclass **Ganoidei** or enamel-scaled fishes.
  Subclass **Teleostei** or bony fishes.

Class Pisces or True Fishes

Subclass Elasmobranchii or Cartilaginous Fishes

The word Elasmobranchii means *having plate-like gills*, and the group includes the ancient and modern true sharks, sawfishes, sea-cats (*Chimæra*), skates, and rays. With few exceptions, the living forms are inhabitants of marine waters (see Pl. 14, Fig. 3).

In most elasmobranchs the mouth is on the under side of the head, but in some it is at the forward end. The internal skeleton is cartilaginous, with more or less calcification (not ossification, as that implies bony structure), but no members of the subclass have complete bony skeletons. The tail is usually heterocercal. The skin often appears to be naked, but there are always dermal denticles (small pieces) tipped with hard, shining enamel, cored with dentine (phosphate and carbonate of lime with fluoride), and with a bony (phosphate of lime) base sunk in the dermis or deeper part of the skin. This type of scale is called *placoid*, and has the same structure as teeth, which originally also developed out of the skin. When the denticles are small and closely set they constitute the so-called *shagreen* (meaning a rough mosaic).

The five gill slits on either side of the body back of the head are, in living cartilaginous fishes, either open or covered by a skin flap, never by a bony operculum as in most other kinds. The median fins are often provided with long, sharp, horny or bony spines, this being particularly true of the dorsal ones. It is these spines and the teeth of sharks that are usually preserved as fossils; unfortunately, however, they give little information as to the general characteristics of the animals.

The brain is enclosed in a solid cartilaginous box or skull without sutures or joints, and in this feature the elasmobranchs differ from nearly all other fishes (the exception being rarely among ganoids), in which the separate skull bones are easily distinguished. There

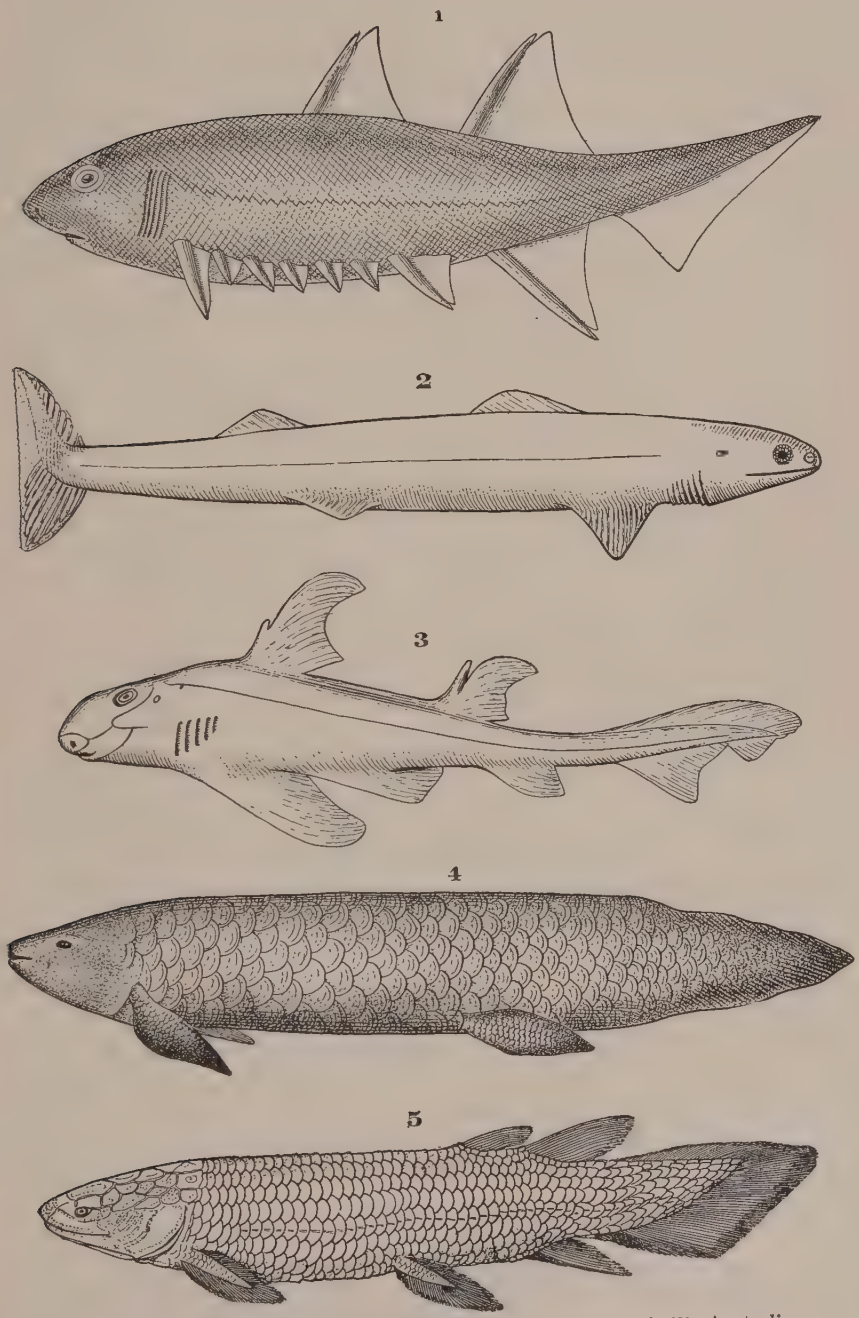


Plate 14. — Devonian sharks (1, 2), living Port Jackson shark (3), Australian lung-fish (4), and Devonian lung-fish (5). See Appendix B.

is no swimming bladder, and the large intestine or rectum is peculiar because it is always provided, on account of its short length, with an internal spiral membrane or fold, which serves to increase the absorbing surface. This is often seen in the fossil forms since Upper Devonian time and it is also present in the lung-fishes and ganoids.

Geologic Occurrence. — In America the oldest fossil evidence of elasmobranchs is that of small fin spines occurring in the early Silurian (Clinton) of Pennsylvania. Other spines occur near the top of the Silurian, and in Europe, where the specimens are more numerous, the oldest are from about the same horizon (Upper Ludlow bone bed). In the American Devonian there are 39 species, in the Mississippian 288, in the Pennsylvanian 55, and in the Permian 10. Therefore there was apparently a very rapid evolution

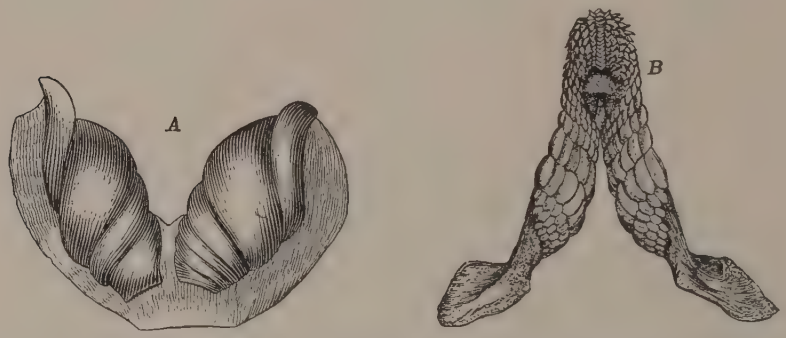


Fig. 406. — Cochliodont (*A*) and cestraciont (*B*) teeth of primitive sharks. *A*, jaw with two large tooth-plates (*Cochliodus contortus*). *B*, upper jaw, with many teeth, of Port Jackson shark (*Cestracion philippi*). British Museum (Natural History).

of the sharks in the Mississippian, when they were the dominant marine fishes, and a quick decline immediately afterward, the history being the same in Europe. These sharks were nearly all of primitive types, that is, the acanthodians were least in number, and by far the commonest were those with pavement-like teeth, known as cestracionts, and the cochliodonts (Fig. 406). The acanthodians (defined on the next page) vanished with the Paleozoic, while the other forms were very sparingly represented after Permian time.

The modern sharks appeared in the early Mesozoic and were common in the Cretaceous, attaining their climax in the Miocene, but the stock was greatly reduced by the cold waters of the Glacial period.

The *acanthodian* (*spinous*) *sharks*, which were of small size, rarely exceeding a foot in length, are particularly common in the Old Red deposits of Scotland, but are also known in Paleozoic marine strata since the Upper Silurian (see Pl. 14, Fig. 1). They are differentiated from the true and most other Paleozoic sharks by their placoid skin, in which are embedded small, flattened, closely fitting, bony plates composed of dentine and enamel, and by the further fact that the stout spines are not restricted to the median fins but are also developed in connection with the paired fins. The teeth are small and rather of the pointed type like those of modern sharks.

The term *Selachii* is taken from the Greek and means *sharks*. The order includes the large, active, more or less spindle-shaped sharks, the saw-fishes, and the flattened, sluggish, bottom-living rays and skates of the present time

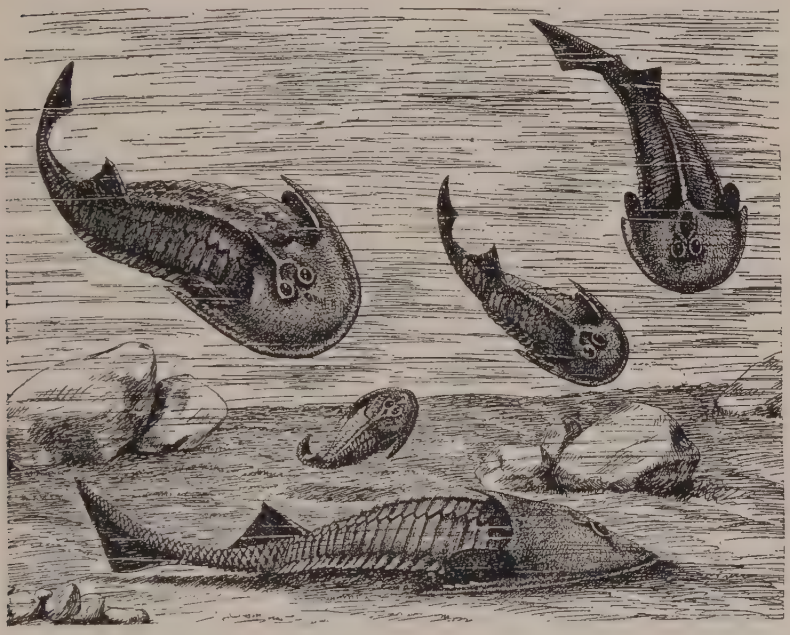


Fig. 407. — Small armored fishes (Ostracodermi) restored (*Cephalaspis*). Lower Devonian of Europe. After Koken, from Museum Guide of University of Tübingen.

and of the Tertiary and Mesozoic eras. The Paleozoic forms of this order are the two families known as cestracionts and cochliodonts. The first group is best represented by the Port Jackson shark, which lives off South Australia (see Pl. 14, Fig. 3), and is characterized by having two stout dorsal fin spines and, in the deeper parts of the mouth, many blunt and pavement-like teeth adapted for crushing shellfish and crustaceans (therefore also known as the "oyster crusher"). In the cochliodont sharks the individual teeth are fused into two large plates whose upper surface has spirally curved ridges suggesting the spirals of snail shells, the characteristic that gave rise to the family term (see Fig. 406). It is these hard parts that are so often seen in the later Paleozoic and far

less commonly in the Mesozoic; the cochliodonts, however, vanished with the Carboniferous. The sharp-cutting type of tooth seen in modern sharks was not common in the Paleozoic, but since the Cretaceous it has been abundant. In the Miocene of South Carolina occur teeth of this type, the largest of which are nearly 6 inches in length (*Carcharodon*), indicating sharks with a length of 60 feet. The living Great Blue Shark attains to 40 feet in length.

Subclass Ostracodermi or Bony-skinned Fishes

The small group of ostracoderms (means *bony-skinned*), or armored and possibly highly aberrant sharks, lived only during the Ordovician, Silurian, and Devonian periods, and represent a line of

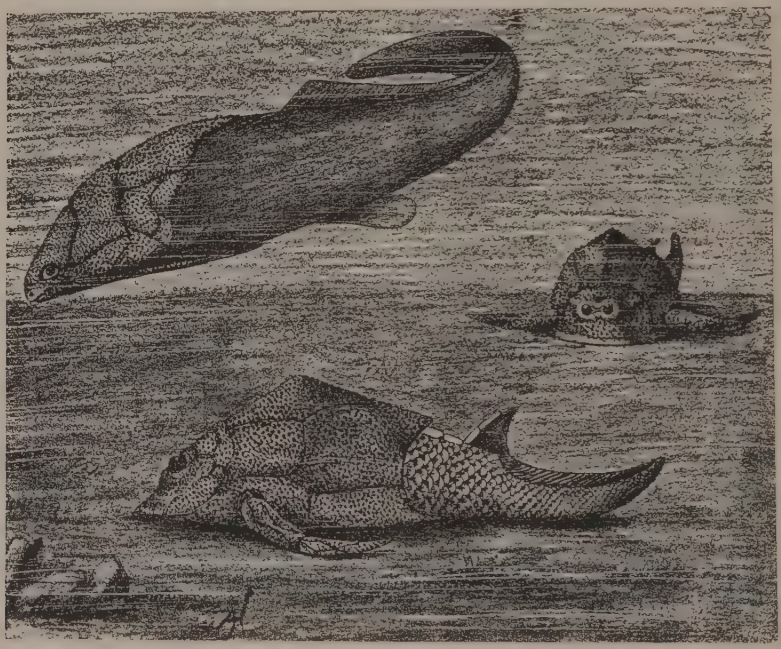


Fig. 408. — Devonian armored fishes (Ostracodermi), having a pair of swimming paddles (*Pterichthys*), shown in the two lower figures. The upper figure is an armored marine lung-fish (*Coccosteus*), one of the Arthrodira. After Koken, from Museum Guide of University of Tübingen.

fish evolution in the wrong direction, for they have left no descendants. They are, in fact, so different from other true fishes as to make it impossible as yet to indicate their relationship to other vertebrates. The subclass includes the oldest known fishes and is thought to be a highly aberrant stock of cartilaginous sharks. The ostracoderms were probably bottom-feeders and of sluggish habits, apparently living in the lagoon areas of the seas and in the

rivers. The head and anterior body was large, broad, and depressed, and armored by small placoid plates or scales, which were sometimes fused into more or less thick bony plates, while the posterior region was either naked or more or less covered by similar plates or scales. The tail was heterocercal, and there was no internal skeleton (see Figs. 407, 408).

In structure and form, there was considerable variety among the bony-skinned fishes. The older kinds, of very diverse construction, were without a pair of lateral paddles or swimming limbs (*Pteraspis*, *Cephalaspis*, *Drepanaspis*), and the eyes were either far apart or set closely together (see Figs. 407, 408). Restricted to the Upper Devonian, and probably to fresh waters, occur the forms with anterior armored paddles, decided armor over the anterior region, and eyes closely set (*Bothriolepis*, *Pterichthys*, Fig. 408). It is possible, however, that the latter genera do not belong in this subclass. The ostracoderms are widely distributed throughout Europe and North America.

Subclass Dipnoi or True Lung-fishes

The Dipnoi (from the Greek words meaning *double breathing*) are the "lung-fishes," so termed because the three living genera have an air bladder which opens into the mouth and which is either single or double, with numerous cellular spaces. This is an outgrowth of the anterior region of the digestive tract and serves as a lung, supplementing, and in times of drought supplanting, the functions of the gills as organs of respiration. From an evolutionary standpoint, the lung-fishes are very important, because the air bladder is comparable with the lung of the higher vertebrates in that it returns the aërated blood direct to the heart, whereas in most other fishes the blood is carried from the air bladder through the general circulation before reaching the heart. The nasal sacs are on the exterior of the snout and open into the mouth, a condition met with also in Amphibia and higher vertebrates, but very rarely in fishes. It is in the lung-fishes, then, that we see the possibilities for the development of the higher vertebrates, though this does not necessarily mean that they were the progenitors of the latter. In many ways, they are intermediate in structure between the lower fishes and the amphibious salamanders, but they are not the connecting links between the fishes and the amphibians. It is probable that paleontologists will discover in the older Devonian, or possibly even in the Silurian, the stem animals that gave rise on the one side to the lung-fishes, and on the other to the salamander-

like Amphibia known as Stegocephalia. This evolution is further discussed in Chapter XXXIX.

The dipnoans (Pl. 14, Fig. 4) are sluggish animals, rising occasionally to the surface for a new supply of air; in times of drought they encase themselves in a cocoon made of slime and clay, and breathe air through an opening made in the mud. In this condition, and without food, some can live for eight months. In the living forms there are also either two or four pairs of gills covered by a movable bony operculum. They are generally eel-like in appearance, with the dorsal and ventral median fins usually continuous with the tail fin. Among the Devonian forms the tail is usually of the heterocercal type (Pl. 14, Fig. 5), but in recent forms it is diphycercal (Fig. 4). The paired fins are long, broadly lobed, muscular, scaled, and fringed in the Devonian species and in living *Ceratodus*, but in other modern forms they are very slender, pointed, and without the fringe. The body is covered with overlapping *cycloid* scales, that is, thin, elastic, circular plates of phosphate of lime, but without enamel.

Dipnoans are cartilaginous fishes in which there is, however, some ossification, but they have no vertebræ differentiated as such. The skull consists of cartilage covered by a variable number of membrane bones that are thickest in Paleozoic genera. These are superficial bones developed in the membrane covering the cartilage, and are not formed in the cartilage itself. The teeth are few in number, usually in three pairs, of which two sets are large crushing plates. The food consists in the main of crustaceans, shellfish, frogs, worms, and insects, along with water plants. The intestine has a spiral valve similar to that in elasmobranchs.

The dipnoans are closely related to the fringe-finned ganoids (see page 690), these two types of fishes being the most important offshoots of the primitive sharks. The oldest dipnoans, in about fifteen species, occur in the Devonian of both Europe and America.

Subclass Arthrodira or Armored Fishes

The term Arthrodira means *jointed neck*, and is given because the armor of the head slides somewhat over that of the body, thus allowing the head to move up and down, a rare feature among fishes, seen only in this class and among the bony-skinned type (Figs. 408, 409). Arthrodira were more or less heavily armored animals whose relationship to the other fishes is unknown. The great majority were marine, the group having gone to sea from fresh water before Devonian time. In America they were the

largest and fiercest fishes of this time, but died out in the earliest Mississippian. They had no true teeth; the structures functioning as such were large cutting shears or crushing plates and were few in number. The tail was heterocercal and there appears to have been a pair of pelvic fins. Of an internal skeleton there was little, for

Fig. 409. — The "terrible fish" (*Dinichthys*), an arthrodire from the Upper Devonian of Ohio. *sl*, sliding joint, the feature that gave rise to the name Arthrodira. Original in American Museum of Natural History.

the vertebral axis was not bony, though the neural and ventral arches were somewhat ossified.

The Arthrodira easily dominated the aquatic life of the Devonian seas, one American form, *Dinichthys*, the "terrible fish," attaining a length of over 20 feet (Fig. 409). There are more than forty species known in North America, and one locality in Germany (Wildungen) has alone yielded upward of fifty forms.

Subclass Ganoidei or Enamel-scaled Fishes

The term Ganoidei, which means *bright appearance*, has reference to the glossy surface of most of these fishes, as, for instance, in the living gar-pikes (see Pl. 13, Fig. 1). This glossiness is due to the more or less thick rhombic scales found in gar-pikes or the cycloid-like scales in Devonian forms, which are covered with bright enamel of the same character as the outer covering in teeth. The ganoid scales differ from the placoid scales of elasmobranchs in that they have but two layers, an outer enamel and a thicker bony layer beneath. In some ganoids, however, there are true elastic cycloid scales (see Pl. 13, Fig. 4). The ganoids are essentially fresh-water fishes, although some are marine and only ascend the rivers to spawn. In the geologic past the marine members seem to have been considerably more common than now. The best known living examples are the sturgeons and gar-pikes, but the origin of the subclass goes back at least to the Lower Devonian, for they are common in the Old Red sandstone (see Pl. 13, Figs. 2–4)

and continue to be abundant until early Cretaceous time. In their organization they form a connecting link between the sharks and the bony fishes.

The skull is well protected by dermal bones or is completely ossified, and while the interior skeleton is more or less bony, there are some forms in which it is wholly cartilaginous. In this subclass appears for the first time the perfected fish mouth, in which the lower jaw operates against the teeth of the perfected upper jaw, as in the higher vertebrates. An air bladder is always present and is connected with the gullet; in the gar-pikes it assists in respiration but is never cellular as in the lung-fishes. There is a spiral valve in the intestine, and the tail is heterocercal or diphycercal.

Fringe-finned Ganoids. — According to the character of the fins, the ganoids are divided into two orders, namely (1) the fringe-finned or lobe-finned ganoids (Crossopterygii), and (2) the pillar-finned ganoids (Stylopterygii). Those of the first order are essentially fresh-water fishes and have thick, muscular, scale-covered, lobe-like limbs fringed with a marginal membrane as in some lung-fishes. Of this order there are but two genera, both of which live in the fresh waters of Africa. Even though their air bladder also functions as a lung, these fishes cannot live out of water more than three hours. They were the common fishes in the Lower Devonian, the best known forms being the genera *Holoptychius*, *Eusthenopteron*, and *Osteolepis* (Pl. 13, Figs. 2–4). In these ganoids the layers of bone of the conical teeth are often deeply and complexly folded or labyrinthine, and in this are particularly interesting because the same kind of teeth occur in all of the Paleozoic amphibians. This similarity of tooth structure is another hint showing the common origin of the Devonian fresh-water fishes and the Amphibia.

Pillar-finned Ganoids. — The more modern or pillar-finned ganoids differ from the fringe-finned forms in that the limbs have not the thick, muscular, scale-covered lobes, but are more like those of the higher or bony fishes. They also occur in the Devonian but are the rarer forms of ganoids in the Paleozoic. In the marine deposits of Mesozoic time, and especially of the Jurassic, they occur frequently.

Subclass Teleostei or Bony Fishes

The teleosts (means *true bone*) are the modern fishes and express the highest organization among these animals, for their evolution has tended to complete adaptation to the water (see Fig. 404). Most of the fishes of commerce and sport are of this subclass and occur abundantly in the fresh waters, seas, and oceans. Their origin was in the Ganoidei, apparently in late Paleozoic time, but they were not common until the Comanchian, with their best development in the Tertiary and at present.

The bony fishes are nearly always covered with thin, elastic, cycloid scales, never with placoid, and very rarely with ganoid

scales. In some the skin is naked and slimy. The caudal fin is usually homocercal and the paired limbs are never lobed. The gills are always covered by a movable operculum. The elongated air or swimming bladder, when present, is filled with gas and lies dorsally to the body cavity; it is not a lung but a hydrostatic organ. The internal skeleton is wholly ossified, the vertebræ are hollow at both ends (amphicœlous), there is a bony neural arch enclosing the spinal nerve-cord, and each vertebra has also a pair of ribs enclosing the viscera. Many of these characters are also seen, but less perfectly, in the Ganoidei, and therefore some naturalists regard both subclasses as representing but a single group.

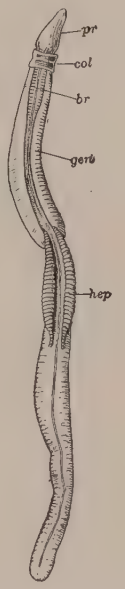


Fig. 410. — The worm-like half-vertebrate *Balanoglossus*, from the dorsal side. After Spengel. *br*, branchia or gills; *col*, collar; *gen*, genital ridges; *hep*, elevations formed by liver lobes (cæca); *pr*, digging proboscis.

Ancestry of Fishes

In spite of the facts that fishes have bony skeletons and that they are known back to the Ordovician, their early ancestors are still undiscovered. Zoölogists are not able to determine this ancestry even among the vast horde of living forms and their embryos, nor have paleontologists, on the other hand, as yet found the "missing links" between the invertebrates and the fishes. The oldest fossil vertebrates are undoubted fishes, seemingly of elasmobranch character, and, while the paleontologist may yet find vertebrates of a lower type, it seems as if the natural conditions are against this possibility, because the earliest vertebrates must have been not only small but also without hard parts.

Among the unsegmented worms (nemertians) one finds the closest approach to the lowest type of vertebrate ancestors in animals often spoken of as half-vertebrates (Hemichordata). The structural gap between them is, however, great. The Hemichordata are worm-like animals, with a distinct head and tail, and breathe through the anterior region of the intestine (intestinal breathers). In this group we see in *Balanoglossus* the rudiments of the future gills, the breathing organs of fishes (see Fig. 410). Further, the main nerve-cord is situated dorsally and the intestinal tract ventrally, and these

are the fundamental structures around which the vertebrate organization has been evolved.

Balanoglossus burrows in sand and mud in almost all seas and attains a greatest length of 6 inches. The anterior end is formed of the burrowing proboscis, beneath which on the ventral side is the mouth, followed behind by the collar, then the region of gill slits, and finally a long, soft, slightly coiled portion. There is a dorsal nerve-cord, often tubular, and like a typical spinal cord. The dorsal region of the pharynx is respiratory and the water passes through the gill slits, which open dorsally on the exterior. These gill slits have chitinous skeleton bars.

The next step is seen among the sea-squirts (tunicates). These animals, however, are greatly degenerate in adult life, due to their sedentary habit, and their vertebrate affinity is only shown in the earliest stages of growth (see Fig. 411). They are on the border line between the invertebrates and vertebrates. Their tiny larvæ are free and active animals, strongly resembling the next higher known stage in vertebrate evolution, the lancelets, described below. What is so important in the larvæ of the sea-squirts is that they have in addition to the hemichordate structures a true notochord in the tail, the notochord being the rudiment out of which the vertebrated backbone of the higher vertebrates has evolved. Sea-squirts are therefore spoken of as primitive chordates (Urochorda), that is, vertebrate animals with the most primitive type of backbone, which, however, is not bone, nor even cartilage, but a gelatinous unsegmented material. The spinal cord or trunk nerve lies above or dorsally to the notochord.

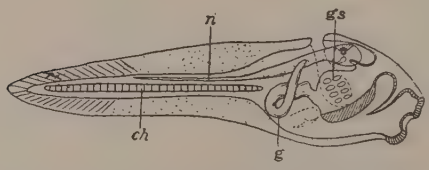


Fig. 411. — Sectional diagram through a tunicate embryo (*Clavellina*). Modified from Seeliger. *ch*, notochord; *g*, gut; *gs*, gill slits; *n*, nerve-cord beginning to degenerate.

The larva of a tunicate is not unlike the lancelet and has a dorsal nerve-cord, a notochord in the tail region, gill slits opening from the pharynx, a branchial chamber that in turn opens into an external aperture, and an eye developing from the brain. In its development the promise of youth is unfulfilled; the active larva settles down to a sedentary life, loses tail and notochord, nerve-cord, and eye, and becomes strangely deformed.

Lancelets (lance-shaped) represent the third great step toward the perfection of the vertebrates, but are an offshoot from the main line of ancestors to the fishes. Nevertheless, they are "a prophecy

of a fish " and in them the notochord is well developed as a cylindrical rod of notochordal tissue. However, it is not yet cartilaginous (see Figs. 412, 413). From the lancelets to the cyclostomes,

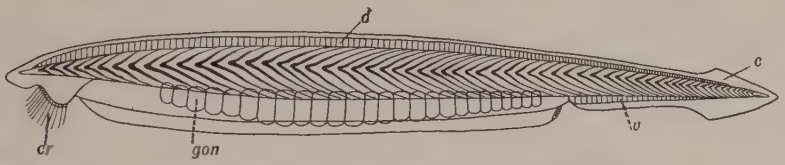


Fig. 412. — The lancelet (*Amphioxus lanceolatus*), " a prophecy of a fish." After Lankester. *c*, caudal or tail fin; *cr*, sensing cirri around mouth; *d*, dorsal median fin; *gon*, gonads or reproductive organs, as seen through the transparent body; *v*, median ventral fin. The V-shaped markings show the exterior muscles.

practically all of the many intermediate evolutionary steps are lost. Similarly, many steps are lost between cyclostomes and the true fishes.

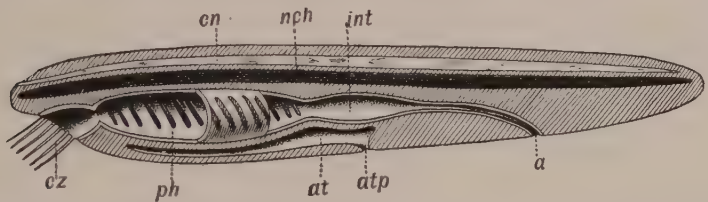


Fig. 413. — The lancelet sectioned to show the internal parts. From Boas's *Lehrbuch*. *a*, anus; *at*, atrium or passage into which the water passes from the gills and then passes out at the atriopore (*atp*); *cn*, central nerve or spinal cord; *cz*, cirri around vestibule that opens into mouth; *int*, intestine; *nch*, notochord; *ph*, pharynx, seen from inside and outside, through which pass the gill slits.

Lancelet or Amphioxus. — In the living world there are about sixteen widely distributed species of lancelets living near the coasts in warm and temperate seas, but no fossil lancelet is yet known. These are vertebrates reduced to the very lowest terms. The animals are sluggish in habit, living somewhat buried in the sand, and ranging in length from 0.5 to 4 inches. They feed on microscopic organisms or organic particles.

In general form these little animals are fish-like, but they are widely removed from the fishes by the absence of limbs, skull, jaws, differentiated brain, eyes, definite heart, spleen, and genital ducts. There is, however, a tubular dorsal nerve-cord, the notochord being persistent, unsegmented, and surrounded by a continuous sheath. The gill slits are very numerous and in the adult there may be as many as one hundred pairs. There is a median dorsal and ventral fin continued around the diphycercal tail. On either side of the body there is a fold often interpreted as a fin fold.

Cyclostomata. — All of the fishes and the higher vertebrates as well are characterized by having articulating jaws, but there are other undoubted vertebrates without jaws which are lower in

structure. These are known as the Cyclostomata. This slightly diversified class includes the fresh-water lampreys and the marine hag-fishes (see Pl. 13, Fig. 5), animals sometimes confounded with the eels (true fishes), though the resemblance between them is only in the general form of the body. They are without jaws and paired limbs, and the skeleton is wholly cartilaginous, except the horny teeth, which are set in the mouth in circular and radiating rows (see Fig. 414). The gills, usually seven in number, are in pouches, the external and internal openings being small.

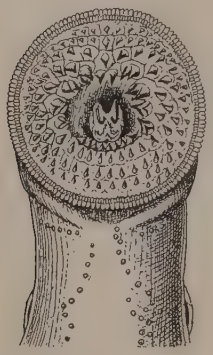


Fig. 414. — Mouth of the lake lamprey, showing rasping teeth, and larger teeth of central tongue. After Gage.

It is not probable that the cyclostomes are in the direct line of evolution to the fishes, but they give at least a good hint of the probable fish ancestors. They are the lowest vertebrate stock with skulls, the lowest class of the subphylum Craniata. The oldest form, if a true cyclostome, occurs in the middle member of the Old Red at Caithness, Scotland

CHAPTER XXXVIII

DEVONIAN TIME AND THE DOMINANCY OF THE FISHES

History of the Term Devonian. — Previous to 1833 the geologic column was not determined beneath the "Carboniferous," the time of the world's greatest coal making. In western Europe, however, it was soon noted that above the coal-bearing strata there lay a great mass of red sandstones and marls, and that beneath the Carboniferous in Scotland occurred a similar mass. Because geologists had not yet recognized the importance of designating type areas of strata by the name of the locality in which they occur, these two divisions came to be known simply as the New Red sandstone (upper series) and the Old Red sandstone (lower series), with the Carboniferous between them. The upper series, because in Germany it has three divisions, was later named Trias, a term now altered to Triassic, but the Old Red sandstone, on the other hand, to this day has failed to yield undoubted marine fossils, and since the geologic column is essentially based on a marine faunal sequence, this lower series did not bear in itself the evidence for correlating it with marine beds. However, not far away from the Old Red area of Scotland, in Devonshire, southern England, there had been collected a number of fossil corals; these were placed in the hands of Lonsdale, and he, in 1837, expressed the opinion that they were intermediate in character between those of the Silurian and the Carboniferous, and, further, that the limestones of Devonshire were of the age of the Old Red sandstone.

This important information was imparted in the same year to both Murchison and Sedgwick, geologists to whom we owe, as has been said in earlier chapters, the first determination of the actual sequence of the Paleozoic strata beneath the Carboniferous. In 1839 these two workers concluded that certain of the marine strata of Devonshire were in all probability the equivalent of the Old Red, and that they occupied a stratigraphic position between the Silurian and the Carboniferous, so, fearing that the New York state geologists would soon propose a period name for equivalent formations, they hastened their work, and in the same year defined the period term Devonian. In the type area in southwestern

England to this day the base of these rocks is not to be seen, and a worse region for the erection of a period term could hardly have been selected. The Devonian here was seen eventually to consist of an immense series, 10,000 to 12,000 feet thick, of graywacke, slate, and limestone, with intercalated eruptives and beds of tuffs. All these are decidedly folded and very much faulted, so that the stratigraphic sequence could only be made out on the basis of the equivalent strata of the continent of Europe. This inherent difficulty was soon recognized by Sedgwick and Murchison, and they crossed the channel and began work in the Rhine valley of Germany, where there is one of the best known developments of Devonian faunas. Their results on this area were published in 1842, but although nearly all the strata studied by them are now recognized as Devonian, at that time they referred most of the rocks to the Cambrian and Silurian. In practice, all Devonian correlations are still made with the Rhine area, although the period name is based on the sequence in Devonshire. If our English cousins had waited until 1842, this period would now be called Erian, and the state of New York would be the type area, than which there could have been no better, even in Germany.

American Devonian

The strata making up the Devonian system in North America have a very wide distribution, especially those of the Middle Devonian, the Lower Devonian rocks being restricted to the margins of the continent (see Pl. 15). Because of this distribution, the Devonian strata of the interior of the continent are, by their faunal content, readily distinguished in the field from the Silurian, but their separation from the Carboniferous above in the Mississippi valley is not so easy. In this interior region the strata are all conformable upon one another, and the disconformities separating the systems can, as a rule, only be determined by the aid of the faunas (see Fig. 415). In the Ohio and Mississippi valleys also the Devonian often terminates in a black shale series and the Mississippian system as often begins with a very similar formation (see Fig. 369). Almost nowhere are there angular unconformities between them.

The longest sequence and the thickest series of Devonian deposits occur in the northern Appalachian area, where most of the materials are shales and fine-grained sandstones. The Catskills on the west side of the Hudson River are the most imposing single Devonian pile in the United States. Another fine Devonian section occurs

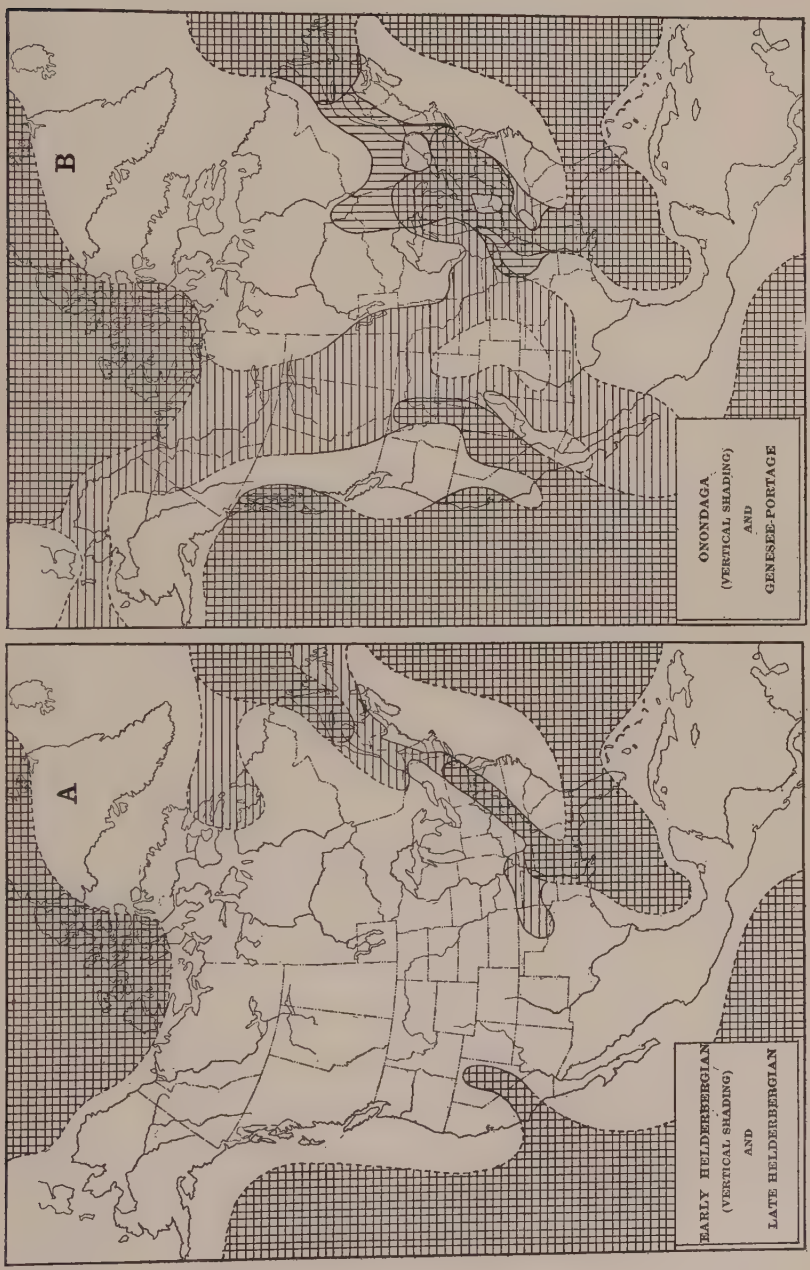


Plate 15. — Devonian paleogeography.

at Gaspé on the end of the peninsula bordering the St. Lawrence River on the south, where the basal 2000 feet of limestone, of Lower Devonian time, are followed by 7000 feet of Middle and Upper Devonian sandstones. Elsewhere in the Maritime Provinces of Canada and in the New England States, the Devonian is poorly represented, and when present consists almost entirely of continental deposits. In the region of the former Cordilleran sea of the United States these formations are never prominent except in Nevada, where, in the Eureka district, a thick section of them is found. In the area of the Canadian portion of this sea there is a good de-

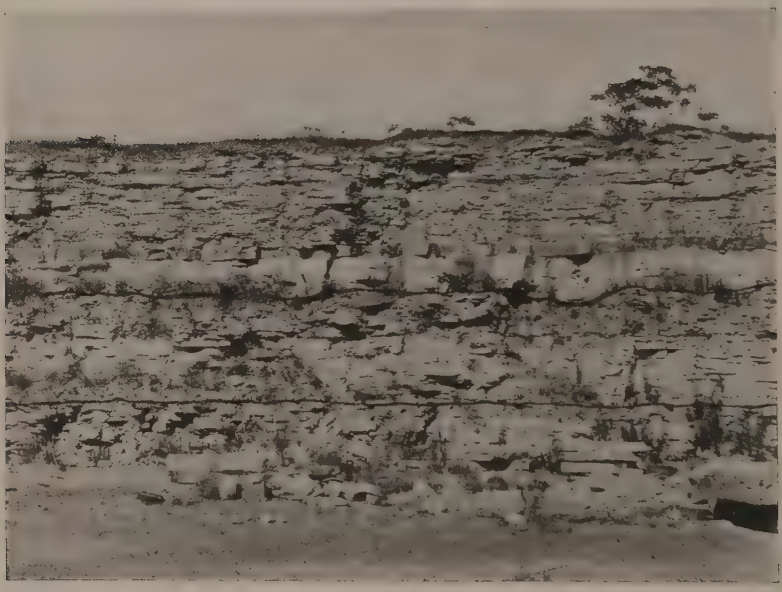


Fig. 415. — Devonian-Silurian disconformity, Buffalo, N. Y. The Middle Devonian (Onondaga) limestone rests on the Silurian (Manlius); below is shown another break (Manlius-Bertie).

velopment of Middle and Upper Devonian, not only in the western mountains but especially to the east of the Cretaceous deposits in the Mackenzie valley and in Manitoba.

Devonian Localities. — The Devonian strata may be seen to good advantage in the Catskill Mountains of eastern New York, and for 25 miles west of Buffalo along the shore of Lake Erie in the western end of the same state (see Fig. 415). About Cumberland, Maryland, almost the entire New York sequence is repeated. Cleveland, Ohio, stands on Upper Devonian, and Sandusky and Columbus, also in that state, on Middle Devonian deposits. Louis-

ville, Kentucky, is famous for its Middle Devonian coral reef. Milwaukee, Wisconsin, and Davenport, Iowa, are good places for fossils of this period. In Michigan, at the summer resort Petoskey, and more especially at Alpena, and in western Ontario about Thedford may be found especially fine Middle Devonian organisms.

The Devonian system in New York is the best known and is therefore the standard for reference in correlation. It is divided as follows:

Upper Devonian	Chautauquan	Chemung-Catskill groups
	Senecan	Portage-Naples-Ithaca groups
		Genesee-Tully groups
Middle Devonian	Erian	Hamilton group
		Onondaga group
Lower Devonian	Oriskanian	Esopus-Oriskany groups
	Helderbergian	Becraft-New Scotland-Coeymans formations

Movements in Appalachia and Acadia. — The great southeastern land Appalachia appears to have been elevated somewhat during the Oriskanian, with more rapid erosion, for there is considerable sand in the deposits of this time in southeastern New York, Pennsylvania, Maryland, and West Virginia, which became coarser as time progressed. Finally, during the earlier part of Onondaga time, some land was added along western Appalachia as a foreland, but all of it was resubmerged before Hamilton time. From this evidence it is thought that, while Appalachia was moved somewhat during the Lower Devonian, the movement was not of a marked character, and the land remained a lowland throughout this period.

Shickshockian Disturbance. — The Acadian mass, however, throughout the New England States and the Maritime Provinces of Canada, began to be moved, that is, elevated and folded, in Middle Devonian time, and the sea was finally completely drained throughout the entire area, destroying forever the seaways that formerly connected the Central Interior sea with the St. Lawrence trough. This movement continued to the end of Devonian time, since even the Upper Devonian strata, of continental character, are folded. Throughout the Devonian, and especially in the Upper Devonian, volcanic activity occurred here on a large scale, many of the intruded masses being still preserved in the Maritime Provinces. Mount Royal, back of McGill University, Montreal, and the Monteregian hills to the east are volcanoes of this time, but far greater intruded masses are seen in many places throughout New Brunswick and southern Quebec. The igneous masses of the Shickshock Mountains along the northern sides of the peninsula of

Gaspé are of that time, and possibly also the crystalline rocks of the White Mountains of New Hampshire. With this folding, the rivers of Acadia were rejuvenated and erosion was marked during Devonian time, for the detrital materials (muds and sands) now piled up in eastern Pennsylvania and New York with, in places, a thickness of nearly 13,000 feet, are the erosional products of this elevation. In Acadia itself the deposits of later Devonian time are of the continental or Old Red sandstone character and contain land plants and fresh-water fishes.

According to Dawson, throughout Nova Scotia, New Brunswick, and southern Quebec the Carboniferous formations rest with marked unconformity upon the older rocks. This being so, the Acadian disturbance was of greater import than is usually believed by American geologists. This deformation was named Shickshockian by Schuchert in 1914.

In the interior of North America the land was variously warped, but all of the movements were of small amount, and resulted only in making very shallow basins for the Middle and Upper Devonian submergences.

During the Lower and Upper Devonian there was also much volcanic activity throughout western Europe, in Great Britain, western Germany, France, and elsewhere.

Submergences of the Continent. — At the beginning of Devonian time almost all of North America had emerged, and at no time during the Lower Devonian was more than 10 per cent of the continent covered with marine waters (see Pl. 15). The Devonian seas were long and narrow in the Appalachian, Acadian, and Cordilleran geosynclines, the invasion from the Gulf of Mexico lying to the south and west of the Cincinnati uplift and south of the Ozark mass. The waters appear to have been oscillatory and unstable in areal extent, and this is especially true of the Appalachian trough.

Late in Oriskanian time the submergence became markedly positive, and attained its maximum flood in the late Middle Devonian (Hamilton), when at least 38 per cent of North America was covered by the sea (see Pl. 15). The waters spread from the Gulf of Mexico northward along the western side of the Cincinnati uplift and across northern Ohio, united with the Atlantic flood, and the two then spread northward from Michigan into the country of James Bay, an extension of Hudson Bay. The waters were warm, for they brought many coral species which built extensive reefs seen in many places in the limestone deposits. There was also an

Arctic invasion through the Cordilleran sea, but when its flood is compared with that of Silurian time it is seen to have been greatly reduced in width, for there was now no inundation throughout the Hudson Bay region and for a long distance northward, as was the case during the two previous periods. The northern water also had an abundance of corals, this being particularly true for Alaska.

Probable Cause of Submergences. — The great Middle Devonian flood was also common to Europe, Asia, South America, and Australia, the strata in New South Wales alone having a thickness of 10,000 feet. It was one of the greatest of continental inundations, exceeded by only one of the subsequent floods, that of Cretaceous time. Such a flooding of the lands could not have been wholly due to the unloading of the eroded land materials into the oceans, for it was of too great an areal extent. Previously, however, when discussing the Caledonian Disturbance of Silurian time, it was stated that Laurentia and Baltica were welded into one continent by that movement, and it is probable that the shallow pre-Devonian sea lying between Britain, Norway, and Greenland was also destroyed at that time. It is true that this elevation began toward the close of the Silurian, but that it continued into early Devonian time is attested by the marked and long-enduring volcanic activity in Acadia and western Europe. Not only this, but the extremely thick deposits of the Old Red, to be described later, were accumulated in mountain valleys during and immediately after this upheaval, and are further evidence to the same end. Therefore, the displacing of the Norwegian sea by an extensive land area, combined with the unloading of the mountains into the oceans, caused the general water level to rise everywhere and thus brought about the marked inundation of the continents in Devonian time.

Emergence of the Continent. — During the Upper Devonian the seas were gradually withdrawn, first in the southern Mississippi valley and finally throughout the interior of the continent and the Cordilleran area. If there was any water left on the land, geologists have as yet failed to discern its transition strata uniting the Devonian to the Mississippian. Thus nature delimited another geologic period in the history of the earth, and at the close of the Devonian nearly all of North America was again emergent.

The Great Northern Transverse Continent Eria. — We have seen that the Caledonian Disturbance resulted in the making of mountains that extended throughout northwestern Europe. It was then that Laurentia (Canadian Shield-Greenland) was welded upon Baltica (Sweden-Finland), forming the most western part of the great

northern transverse land mass that extended unbroken far into Asia. Therefore, at the very beginning of Devonian time there came into existence an almost circumpolar land, whose only submerged portion lay in the North Pacific, and which was formed by the union of Laurentia, Baltica, and Angara (see Fig. 434). The great Canadian geologist, Sir William Dawson, of McGill University, labored long to make known the plant life of the Devonian, and since he termed it the Erian flora after the Erian rocks in which it is entombed, taking the name from Lake Erie and the Erie division of the New York state geologists, Suess in 1909 gave the continent the name of *Eria*. It is the old ancestral continent of the modern Holarctic region of the zoölogists (see Fig. 434).

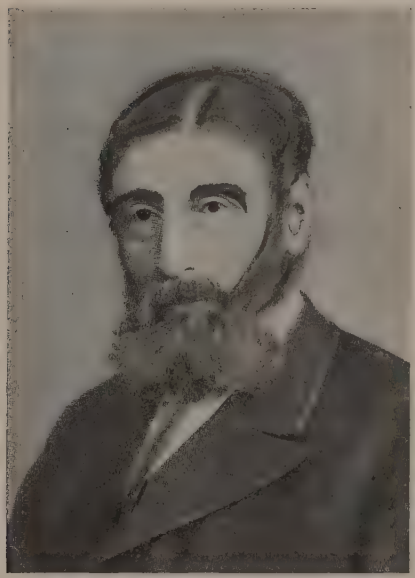


Fig. 416. — Sir William Dawson (1820–1899). One of the founders of Canadian Geology.

Character and Thickness of Devonian Rocks. — *Eastern Lower Devonian Sediments.* — In the Appalachian trough from Virginia to New York the Lower Devonian sediments are well developed, with the most complete section in Maryland, of nearly 900 feet. About one half of these sediments in Maryland are limestones, while the rest are limy sandstones, grading more and more into pure sandstone toward the top. At the base of the Devonian and at the top of the Silurian, the impure magnesian limestones are often sun-cracked, showing the shallowness of these seas (see Fig. 417). Along the Delaware River in Pennsylvania the thickness is over 300 feet in the western area, but about Port Jervis, New York, the series thickens to 1150 feet, of which the upper 550 feet is grit (Esopus), and the rest limestone or calcareous shale. Northward into the foothills of the Catskill Mountains the Lower Devonian decreases rapidly, and only thin and scattered remainders occur west of Syracuse, New York.

Eastern Middle and Upper Devonian Sediments. — The sediments of Middle and Upper Devonian time in the Appalachian trough from southern Virginia north into the Catskills are of great thick-

ness and significance. The greatest thickness is in Pennsylvania, where the Susquehanna River has cut through the Appalachian Mountains; here the Pennsylvania Geological Survey has determined a maximum depth of nearly 13,000 feet of Devonian shales and sandstones, becoming increasingly coarser, redder, less marine, and more rapid in accumulation with the progress of time, that is, toward the top.

To make more evident what is represented in Pennsylvania, some of the details of the section should be given. In this great series, there are from 260 to 425 (Helderbergian 50–100, Oriskanian 210–325) feet of Lower Devonian limestone and arenaceous sandstone. The Middle Devonian starts with the widely

Fig. 417. — Sun-cracked Silurian limestone (Salina), Round Top, Maryland.

spread Onondaga limestone, which has a depth of 0 to 250 feet. Then begins the great detrital series of muds and sands, as follows: Hamilton, 1400 to 2500 feet; Portage, 1100 to 1400 feet; Chemung, 2200 to 4600 feet; and the Catskills, 2500 to 3700 feet. In other words, the Lower Devonian has 260 to 425 feet, the Middle Devonian 1400 to 2750 feet, and the Upper Devonian 5800 to 9700 feet, with most of it red shales and coarse sandstones and conglomerates. The thicknesses in Maryland are: Lower Devonian, 340 to 767 feet; Middle Devonian, 600 to 1650 feet; Upper Devonian, 4600 to 8550 feet.

Appalachian Delta. — Along with the greater rapidity of accumulation the marine faunas become increasingly scarcer upward in the section, and the sediments change in character to red beds,

most of which are of fresh-water origin, marked by ripples, sun-cracks, and rain imprints, and by land plants and land fishes. Pennsylvania was the central area of a great delta formed at the mouth of the large rivers that flowed out of the Acadian highlands, in which latter region there was mountain making and volcanic activity throughout much of the time of the delta accumulation. From this central and rapidly subsiding delta, the deposits thin rapidly to the north, west, and south, in the manner illustrated in Fig. 418.

Devonian Sediments of the Interior. — In the region of the Cincinnati uplift and throughout the Mississippi valley the essentially calcareous deposits, mainly of Middle Devonian time, are very thin when compared with those of the Appalachian region. At Louisville, Kentucky, the thickness is about 60 feet of Middle and 100 feet of Upper Devonian shales, and from here northward, both to the east and west, the sections thicken and introduce more shale, so that in western Ontario there is a depth of about 600 feet, much of which is shale. To the northwest, about Alpena, Michigan, the Middle and Upper Devonian sediments are still thicker, and there are here the greatest accumulations in the medial portion of North America.

In the southern Mississippi valley and in Oklahoma the Devonian sections are thin, and most of the deposits are of Lower and early Middle Devonian time. Probably no single section exceeds 250 feet.

Devonian Sediments of the Western and Arctic Regions. — In the Cordilleran sea the Devonian sediments were essentially limestones, and while the sections within the United States are usually less than 300 feet thick, yet in the Eureka district of Nevada there are from 4000 to 6000 feet of Devonian limestones and calcareous shales. The latter strata seem to represent an unbroken series from the beginning almost to the close of the Devonian period. In Manitoba there are about 400 feet of dolomites, limestones, and shales, and in the Mackenzie valley nearly 900 feet, of which about one half is limestone. From here northward the sections seem to thicken. In southeastern Alaska there are at least 600 feet of limestone. There is another area of sedimentary accumulation in the Ellesmere-Parry Island area, where Per Schei has published a Siluro-Devonian section with a thickness of 8000 feet, most of which consists of coarse Devonian detritals.

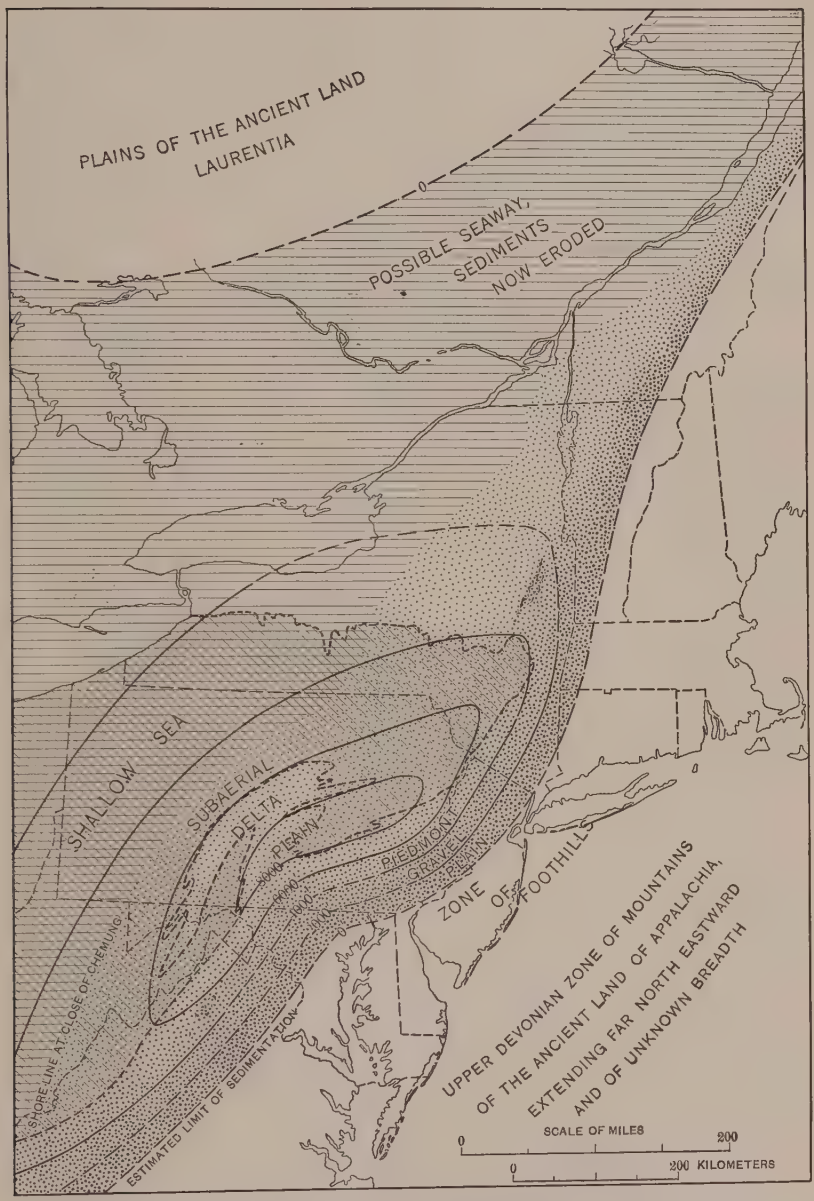


Fig. 418. — Devonian delta of the Appalachian geosyncline, as it probably was at the close of this period. Dotted area that of the fresh-water and brackish-water deposits; horizontal lines, marine deposits. Contours showing original thickness of Upper Devonian sediments. Diagonal lines, the area where the deposits still exist. Drawn by Barrell.

Life of the Devonian

Marine Provinces. — The American Devonian seas on faunal grounds may be arranged in three provinces. (1) In the Appalachian and Acadian areas the northern Atlantic waters dominated and the life was in harmony with that of northern Europe. This evidence is best seen in the Lower Devonian, where many species of the Rhine faunas occur, while throughout the balance of this period European migrants are only found periodically in the Appalachian trough. (2) The Central Interior sea to the west of the Cincinnati uplift was dominated by life that was characteristic of this area and of western Brazil, and it is sometimes referred to as the American faunal realm. There was, however, a great difference between the two hemispheres, for in South America corals were practically absent. (3) The Cordilleran sea was another faunal province with most of its life derived from the northern Pacific or Euro-Asiatic realm, and this biota was also wide-spread in the Arctic Ocean. This province was wholly independent of the Central Interior sea until near the close of Middle Devonian time, when the two seas had communication across Iowa and Michigan. The faunal intermigration, however, was most decided from the western to the eastern basin, and occasionally the bottom-dwelling forms migrated along the northern shore and attained western New York. In the Upper Devonian the faunas again took on a cosmopolitan character, the Euro-Asiatic aspect dominated most of the seas of this time, and its representatives are hence found in all three provinces.

Marine Invertebrates. — The seas after Middle Devonian time swarmed with corals, brachiopods, and shellfish, and in general the life was not very unlike that of the Silurian (see Pls. 16–18). The corals were wide-spread, and are known from Louisville, Kentucky, north into Alaska. The Louisville reef is the one best known; it has a great abundance of species, with cup-corals over 24 inches long and more than 3 inches wide, and compound colonies as much as 8 feet across (see Pl. 16). There were also many bryozoans, but the crinids were comparatively far less abundant and nowhere in America were they extensive makers of limestone, as they were in the Silurian. Of the echinoderm type of animals, the blastids were now common and may have originated in America (see Pl. 16). Starfishes were also at times abundant (see Fig. 419). Trilobites were still abundant, but greatly reduced in variety, there being about twenty genera and over one hundred species (see Pl. 18);

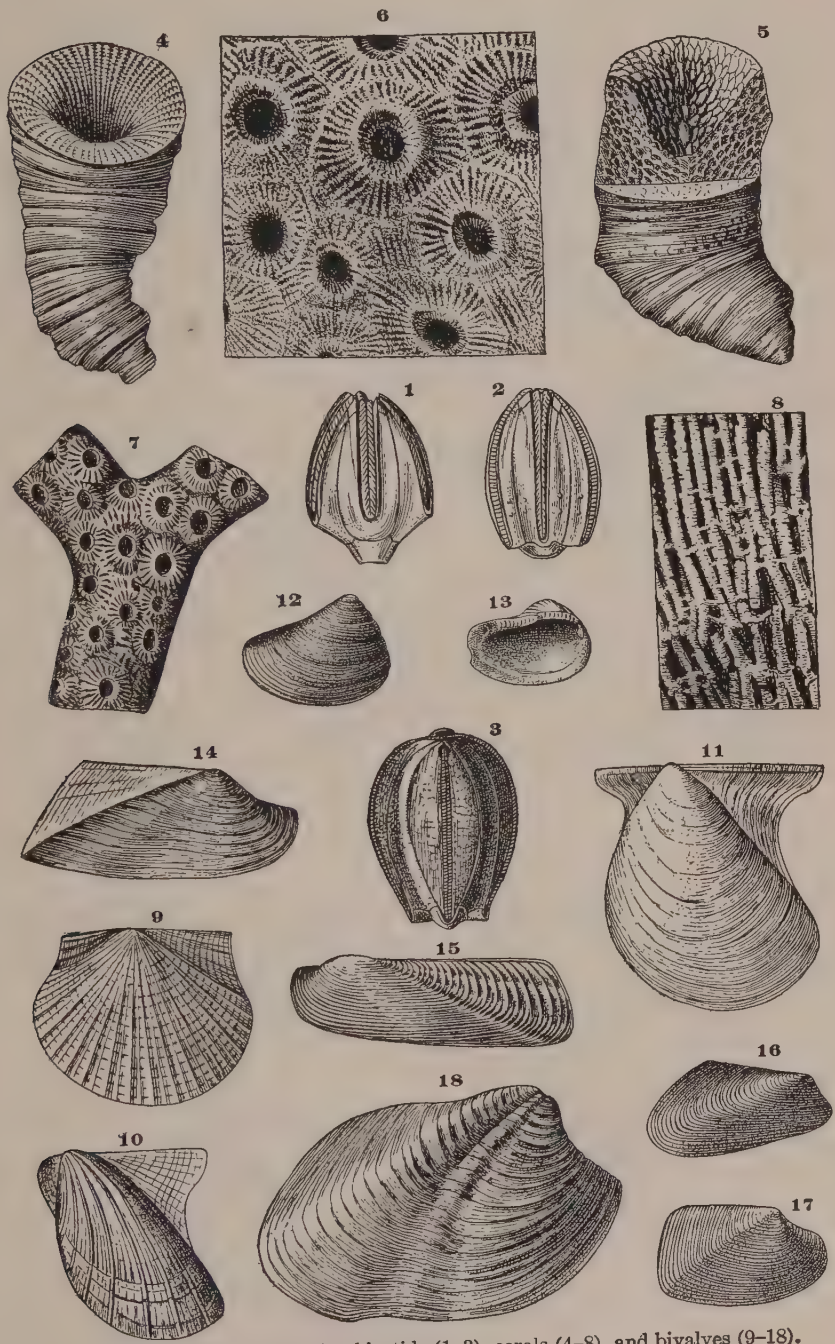


Plate 16. — Middle Devonian blastids (1–3), corals (4–8), and bivalves (9–18).
See Appendix B.

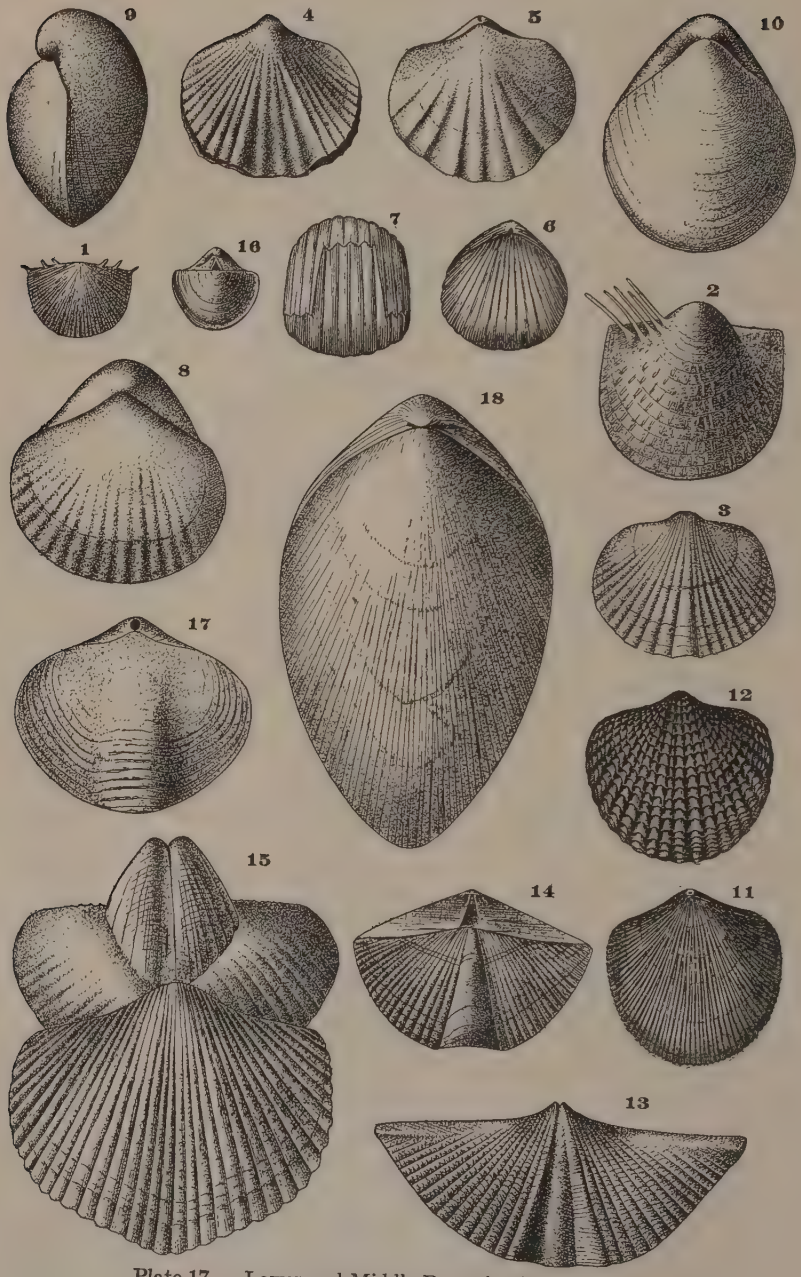


Plate 17. — Lower and Middle Devonian brachiopods.
See Appendix B.

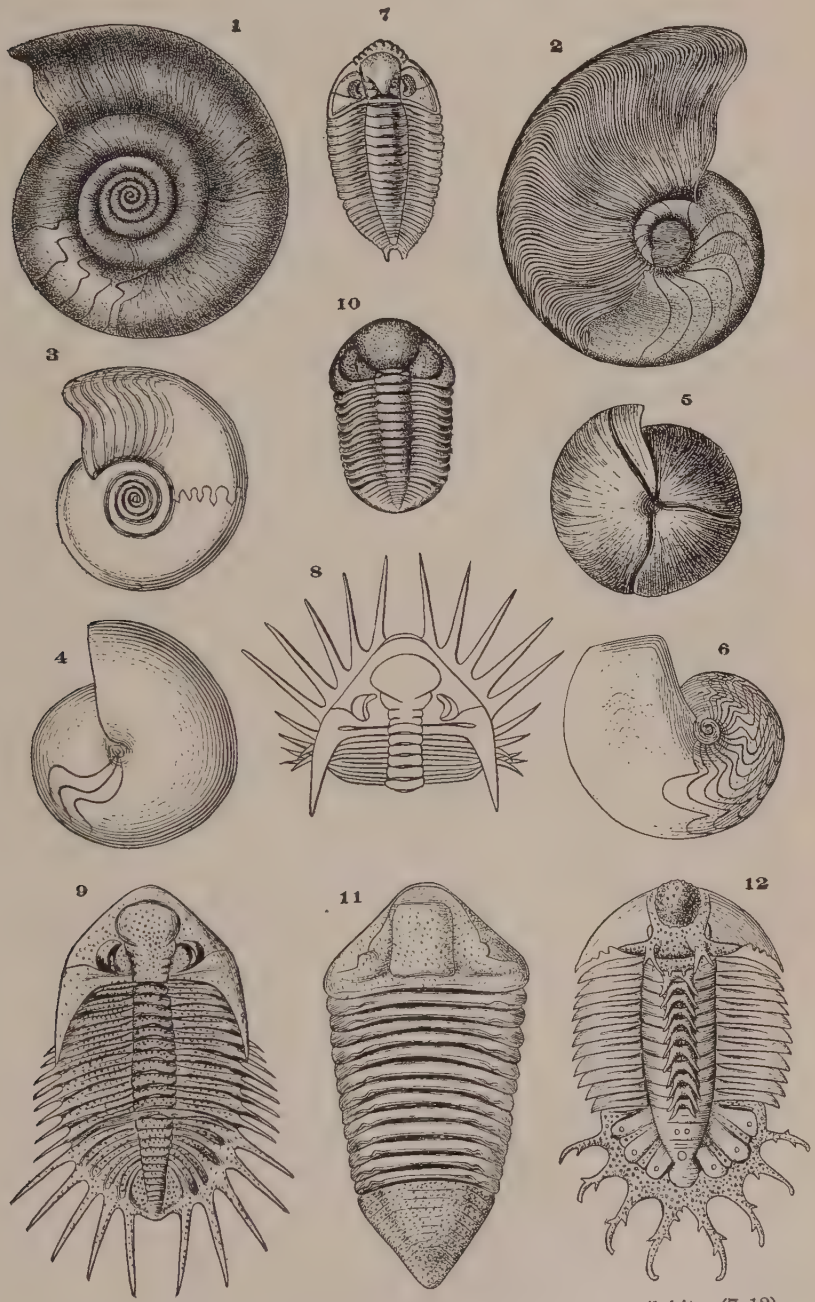


Plate 18. — Middle and Upper Devonian goniatites (1–6), and trilobites (7–12).
See Appendix B.

the most prevalent forms were the bullfrog trilobites (*Phacops rana*), the pointed-tail trilobites (*Dipleura*) and the spiny-tailed ones (*Cryphæus* = *Asteropyge*). The Devonian deposits are often full of brachiopods, of which there were no less than seven hundred

Fig. 419. — Middle Devonian sandstone slab, nearly 5 feet across, from Saugerties, N. Y., with about 200 starfishes (*Devonaster eucharis*) and clam shells (*Grammysia*). Original in New York State Museum, Albany. Photograph from John M. Clarke.

different kinds in North America (see Pl. 17). This was the time of their maximum development and differentiation. The most characteristic were the spire-bearing forms.

Comparing the American marine Devonian faunas with those of Europe, there is seen to be considerable dissimilarity, one especially marked difference being the development in the Old World of the goniatites (see Pl. 18). There these animals appear in six genera at the very base of the Bohemian Devonian and are usually prolific throughout the later part of the period. They continued to be

plentiful in the Mediterranean waters during subsequent Paleozoic time, but in America are usually rare fossils. Goniatites are cousins of the nautilids and gave rise in later Paleozoic time to the ammonids, the most characteristic marine animals of Mesozoic time. Goniatites are described in Chapter XLVIII.

Devonian Fishes. — The fresh waters of Devonian time must have abounded in life, an inference justified by the fact that more than one hundred species of fishes alone are known in the continental deposits of this time. As they are fully discussed and illustrated in the previous chapter, we need here only present a general summary of the Devonian kinds (see Pls. 13, 14). These fishes were primitive in that they did not have well developed internal skeletons, and in that these were more cartilaginous than bony. The median fins were often continuous, or a series of fins, extending along the dorsal and ventral surfaces and meeting around the end of the tail. The vertebral column often extended to the end of the tail, with the continuous fin all around it, a type of tail (diphycercal), nearly always present in the earliest stages of modern fishes. The heterocercal tail was the other common type.

The modern race of bony fishes, such as the perch, cod, and herring, which represent about 99 per cent of all living fishes, had not appeared; on the other hand, the tribe of sturgeons and gar-pike, now almost extinct, made up about a quarter of all Devonian forms; sharks, which are but a small percentage of all living fishes, made up about one third of all the kinds then existing; while, finally, the Arthrodira, a group long extinct and even of uncertain kinship, constituted 40 per cent of the ancient fish fauna. (Dean.)

The ancient marine sharks may have attained a length of from 5 to 6 feet in the Devonian, and dominated the seas of the next or Mississippian period, after which they rapidly declined to the end of the Paleozoic. With the rise of the marine fishes one notes the decline of the trilobites and the nautilids, and it is probable that the fishes fed largely upon both of these types of animals.

Fig. 420. — The oldest amphibian track (*Thinopus antiquus*). $\times\frac{1}{3}$. Upper Devonian of Pennsylvania.

Amphibia. — Of vertebrates higher than the fishes, the only evidence rests upon one foot imprint (*Thinopus antiquus*) nearly 4 inches long, which was found near the top of the Upper Devonian of western Pennsylvania (Fig. 420). This indicates the presence of a salamander-like

animal (stegocephalian) with a probable length of nearly 3 feet. The track is from a marine sandstone of the littoral or beach area over which the animal walked, probably in search of dead marine life. This stratum is associated with others that are ripple-marked and sun-cracked, and bear rain imprints.

Economic Products: Oil and Gas

In the Upper Devonian of western Pennsylvania, West Virginia, Ohio, and New York, vast quantities of petroleum and natural

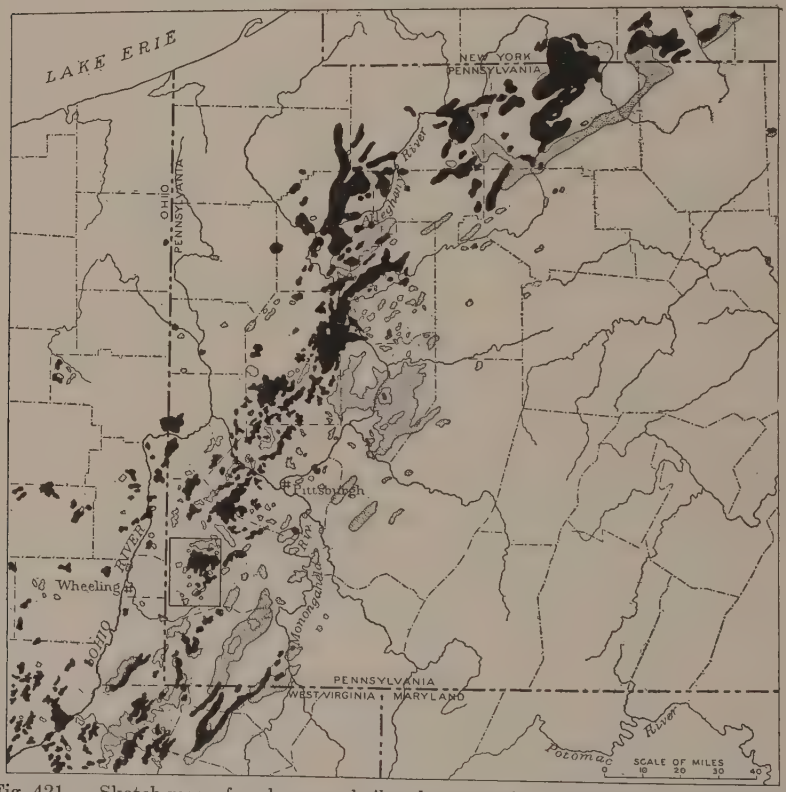


Fig. 421. — Sketch map of underground oil and gas "pools" in Devonian and Mississippian strata of Pennsylvania and adjoining states. Black areas, oil pools; dotted areas, gas. After M. J. Munn, U. S. Geol. Surv.

gas have been obtained by drilling. This was the first exploited field in America, beginning in 1859 with 2000 barrels. During the next forty-five years about 90,000 wells were driven at a cost of about $360,000,000, the yield in that interval being more than 750,000,000 barrels. The field is still productive, more than

twenty distinct horizons yielding petroleum (Oliphant). The map, Fig. 421, shows the areal extent of the underground pools. The oil and gas are stored in coarse, open-textured sandstones and conglomerates, and because of this the term *oil-sand* has come to be applied by drillers to all horizons yielding these volatile hydrocarbons. The number of underground oil-sand layers in a locality varies between one and three, and the productive wells are from 100 to 4000 feet beneath the surface. The oil and gas pools lie parallel to the principal geologic folds of the region (see also pages 637–641).

"Although petroleum as an earth product has been known for centuries, the modern development of the oil and gas industry as well as knowledge regarding the geologic relations of oil dates only from the completion of the Drake well at Titusville, Pa., August 28, 1859. To one familiar with the equipment of to-day, it is hard to realize the difficulties encountered in drilling this pioneer well and that at least one year was consumed in sinking to a depth of 69 feet. Out of this humble and crude beginning have grown the enormous oil and gas industries of the present time, industries that reach to the farthest corner of the globe and involve hundreds of millions of dollars." (Campbell.)

"Drilling with the object of finding new productive territory is of a most speculative nature. Any one of five results may be the outcome of the well when the sand is pierced. (1) The sand rock may be found to be hard and close, incapable of holding oil or permitting the flow of any liquids through its mass; (2) the sand may be good but perfectly dry; or (3) it may be good sand and be completely saturated with salt water, which may fill the well to a depth of several hundred feet or even in some cases flow out upon the derrick floor. Favorable results may have any degree of success. (4) Gas may be found with hundreds of pounds of rock pressure to the square inch and in a volume of millions of feet a day, or there may be only sufficient gas to serve a house or one or two boilers. (5) Oil may be encountered in such quantities and with such pressure that it will gush from the well at the rate of thousands of barrels a day, or there may be only a gradual seeping of oil into the well that will amount to but a barrel or two a day." (Griswold and Munn, 1907.)

CHAPTER XXXIX

THE OLD RED AND THE PROPHECY OF VERTEBRATE DOMINANCE

There is no more significant or picturesque period in the history of the earth than the Devonian. This is the time when the former nakedness of the lands becomes clothed with a deeper verdure and the first forests appear, providing the needed homes and food for the invasion of the continents by the ever-hungry descendants of the denizens of the sea. The conquest is first attained by the invertebrates — the scorpions, shell-fish, worms, and insects. Of greater significance, however, is the adaptation of other marine animals to the land, which eventually leads to the origin of the fishes, the advance guard of the vertebrate hosts, through the development of lungs and the increase in mentality.

The invasion of the land is fairly under way in the Devonian, chiefly in the rivers and lakes, but due to the prevailingly arid climates a fierce struggle is instituted among the inhabitants of the then temporary waters, resulting in the dominancy of the better equipped air-breathing fishes, an issue prophetic of vertebrate ascendancy, hereafter never to be questioned in its onward sweep to its culmination in man.

In the previous chapters we have traced the physical conditions and the perfecting of organic evolution in the *seas* up to the close of Devonian time. In this chapter we must deal with the nature of the Devonian *lands*, their climate, and the character of their life. First we shall trace the rise of the land vegetation and forests, and then take up a further study of the Devonian fresh-water fishes described in the two previous chapters. How, where, and why lungs were developed we shall see by following their history from the gilled and worm-like invertebrates of the sea through the half-vertebrates into the fishes with both gills and lungs, the double breathers, as typified by the lung-fishes of the Devonian.

Continental Deposits

Oldest Fossiliferous Strata. — On page 258 the physical characters of continental deposits and their origin are stated, and now we come to the study of the organic record of such deposits. The

oldest of these strata with fossils are of Devonian time. There are, it is true, undoubted continental deposits as early as the Proterozoic, but they are devoid of fossils. From the Devonian period onward, the geologic record often bears testimony to the continental origin of certain deposits and their entombed life, and while such are preserved and accessible more and more as one goes upward in the geologic scale, still the record of the land-living and air-breathing plants and animals is far more imperfect than the record of marine life. This is due to the fact that the organisms of the land are rarely entombed in the sands and muds of the land waters, but are either eaten by their living contemporaries, or oxidized and blown away by the atmosphere. The life of the fresh waters is more apt to be preserved, along with such land-dwelling organisms as may be accidentally drowned or blown into them (leaves), or washed by the floods into the areas of standing waters where burial may take place. Even though burial occurs on land, however, the circulation of ground waters is far more marked in loose continental deposits than in the more completely cemented marine strata, and in this way nearly all the remains have been leached away.

Old Red of Scotland. — The Old Red deposits of Britain are a tremendously thick series of coarse detritals and volcanic effusives, seemingly accumulated in valleys between high mountains that were upheaved during the Caledonian Disturbance. Jukes-Browne states that there were probably five parallel ranges. The maximum thickness of these deposits may be as great as 37,000 feet, but in no single area is there more than 20,000 feet. Nowhere is there a transition, as has so often been stated, from the Silurian into the Old Red, for the contact is an unconformable one, and the break at the top with the Carboniferous is equally distinct. As long ago as 1856 Godwin-Austen regarded these deposits as of fresh-water origin, a conclusion now agreed to by nearly all geologists. They are probably wholly continental, and were accumulated in several independent and subsiding valleys, under a climate more or less arid (see Fig. 422). The record is a very long one and covers most of the Devonian, though sedimentation was interrupted for a considerable time during the Middle Devonian, and because of this stratigraphic break the Old Red is usually divided into a lower and an upper series. We shall here, however, not follow this two-fold division, but use instead the tripartite arrangement of Goodchild, who has devoted many years to a study of the fossils and rocks in the field.

The *Upper Old Red* has a thickness of 1000 feet in places, and is characterized by the presence of the fish *Holoptychius* (Pl. 13, Fig. 4). The series rests with a marked erosional unconformity upon the very uneven surface of the Lower Old Red and more extensively upon the older upturned and metamorphosed Paleozoic. The rocks are red sandstones, deep red clays and marls, conglomerates and breccias, the sandstones passing into yellow or even into white colors (Geikie). The

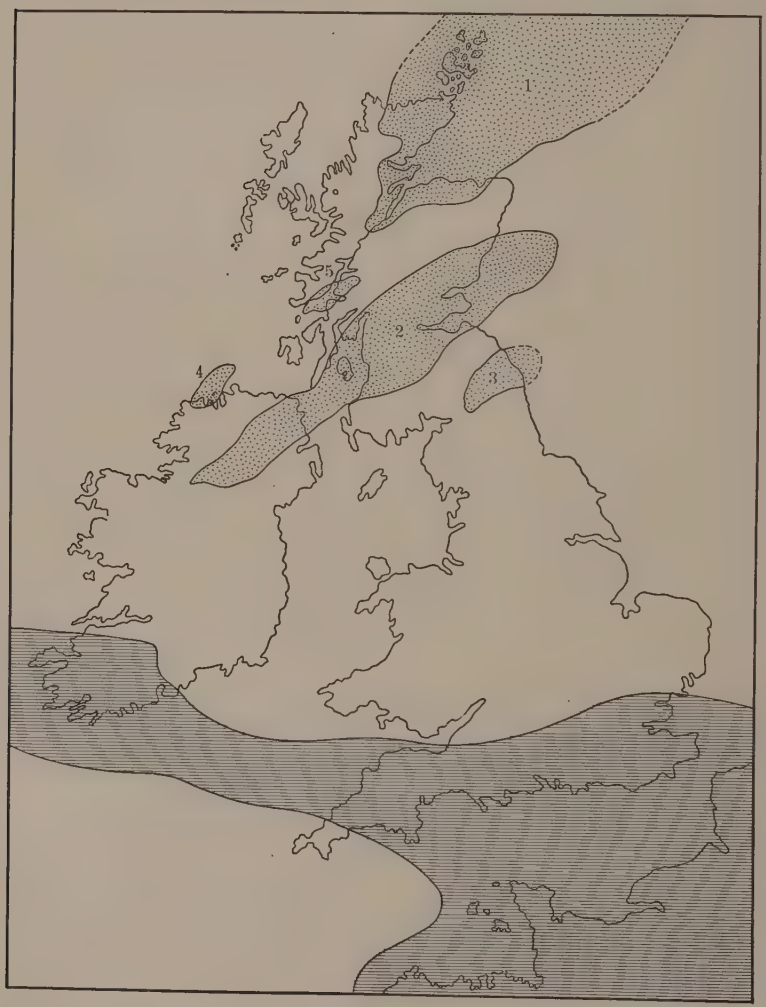


Fig. 422. — Paleogeography of Great Britain in Lower Devonian time, showing the probable relation of the sea (horizontal ruling) to the land (white), and the Old Red lakes of Scotland and Ireland. Modified from Jukes-Browne. 1, Lake Orcadie; 2, Lake Caledonia, 240 × 80 miles; 3, Lake Cheviot; 4, Lake Fanad; 5, Lake Lorne.

series as a whole is remarkably barren of organic remains, but locally there are many fishes thought to have been derived from the upland rivers. The more characteristic of these are the fringe-finned ganoids *Holoptychius* and *Scaumenacia* (Pl. 13, Fig. 3), and the ostracoderms *Asterolepis* and *Bothriolepis*.

The *Middle Old Red* or *Orcadian series* has a thickness of at least 16,000 feet. The series is characterized by the fishes *Dipterus valenciennesi* (Pl. 14, Fig. 5) and *Osteolepis macrolepidotus* (Pl. 13, Fig. 2), and the phyllopod crustacean *Estheria membranacea*. These deposits are best seen on the northern side of the highlands in " Lake Orcadie " in northeastern Scotland, and in Orkney and Shetland. The various separated areas of Old Red deposits, which have been called lakes by Geikie, are distinct " basins of deposits " as described on page 260. Lake Orcadie may have extended as an estuary northeast to Christiania in southern Norway, and possibly even to Petrograd in Russia (Fig. 422).

The dominant color of this middle series is not red, but in Caithness and Thurso in Scotland, where it is well exposed, the deposits consist chiefly of evenly bedded, rippled and sun-cracked, rain-marked, dark gray, bituminous (even impure oil-shales) and calcareous flagstones. These are composed of about 70 per cent of silica, 10 per cent of oxide of iron and alumina, and from 10 to 20 per cent of carbonate of lime. The lower beds of this series, which may be of the age of the Caledonian, are of red sandstones and conglomerates. There are other red sandstones interbedded in the higher parts of the formation. (Geikie.)

Near the middle of the Orcadian series in the Thurso beds occur many fishes, and in the older beds of Achanarras, Stromness and Cromarty as well. About sixty species are known, of which the following genera are most diagnostic: the fringe-finned ganoid *Osteolepis*, the lung-fish *Dipterus valenciennesi*, the armored lung-fish *Coccosteus*, and the ostracoderm *Pterichthys* (Fig. 408).

In Caithness also are found the following land plants: the herbaceous lycopods *Psilophyton* and *Lycopodites milleri*, the small lycopod tree *Lepidodendron nothum*, the tree-fern *Caulopteris peachii*, and the Equisetale or scouring rush *Pinnularia*.

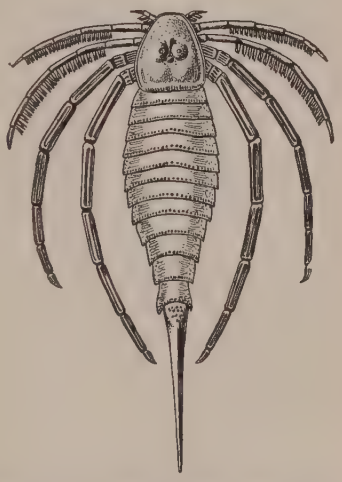


Fig. 423. — The large spike-tailed eurypterid (*Stylonurus excelsior*). $\times \frac{1}{24}$. After Clarke and Ruedemann.

The *Lower Old Red* or *Caledonian series* has a thickness ranging up to 20,000 feet, with the base and top not seen. The characterizing fishes are the ostracoderms *Cephalaspis* and *Pteraspis* (Fig. 407). This series is best developed in the area to the south of the Scottish highlands in " Lake Caledonia " of Geikie. It is preëminently the Old Red of Scotland and occupies the country known to the Romans as Caledonia. Goodchild states that the whole of this vast formation was accumulated under continental conditions, partly in large inland lakes, partly as torrential deposits of various kinds, partly as old desert sands, and partly as the result of extensive volcanic action.

The highest subdivision consists of unfossiliferous, reddish brown or chocolate-colored conglomerates, gray and yellow sandstones, red shales, and gray flags

with occasional bands of limestone, the whole forming the lowland tract of Strathmore. These youngest deposits may yet be shown to be equivalent in age to the lowest beds of the Orcadian series. The middle subdivision consists chiefly of volcanic rocks, mostly andesitic lavas with some tuffs, interbedded with sedimentary strata, attaining a thickness of more than 6000 feet. The lowest division, which has much the appearance of Silurian rocks, consists of graywackes, flagstones, and mudstones.

Near the top of the middle division, but away from the regions of volcanic rocks, have been found myriapods, the lycopod *Psilophyton*, and about twenty species of fishes. The more diagnostic of these are the ostracoderms *Cephalaspis lyelli* (Fig. 407) and *Pteraspis mitchelli;* the acanthodian sharks *Mesacanthus mitchelli*, *Diplacanthus gracilis*, and *Climatius* (Pl. 14, Fig. 1); and the armored shark *Thelodus*, which holds over from the Silurian. At Arbroath are also found an abundance of eurypterids, the best known of which are *Pterygotus anglicus* and *Stylonurus ensiformis* (like Fig. 423).

Old Red in America. — In America there are no fresh-water deposits of Devonian time that were accumulated in inland mountainous areas, like those of Scotland. They are, rather, delta deposits formed by large rivers flowing into the sea, apparently under a semiarid climate. Two of the non-marine animals are shown in Figs. 423 and 425. Clarke regards certain of the Upper Devonian deposits of New York (Oneonta and Catskill) and the sandstones of Gaspé in lower Quebec as of a great coastal lagoon receiving terrigenous sediment rapidly and in vast quantity from the highly elevated old land. In places there are thin, interbedded, marine zones that represent the overwash in times of stress of the outside water bringing in the marine organisms as we find them — sea shells from the littoral. It is in these regions that are found the American Old Red fishes, most of which appear to have come from the rivers and not from the sea. The deposits of Scaumenac, Quebec, which are evenly bedded, gray to greenish, sandy shales, appear to be wholly of fresh-water delta origin, the only fossils being land plants and fishes, in harmony with those of the Upper Devonian of Scotland. There occur eleven species of fishes (selachians three, ostracoderms three, arthrodires one, dipnoans one, ganoids three). No marine fossil of any kind has ever been seen. Not far away, at Campbellton, New Brunswick, however, the deposits are of Lower Devonian age and laid down under the influence of the sea, for here occurs a brecciated limestone holding apparently marine organisms, such as ostracods, fragments of a large *Pterygotus*, *Spirorbis*, and pelagic gastropods (*Cyclora*). Associated in the same formation occur five genera of land plants and nine of fishes (ostracoderms two, arthrodires one, selachians six).

Proof that the Old Red of Scotland is of Continental Origin. — These deposits are often very decidedly cross-bedded, and the

materials are usually poorly assorted. The conglomerates are frequently of great thickness, with erratic bowlders as large as 8 feet in diameter. Ripple-marking is frequent, and the sun-cracking is deep, indicating that there was long exposure to dry air, since the edges of the prisms are often curled. There are also present rain-drop impressions. All of these are characteristic of continental deposits. While the rocks are not red throughout the Old Red series, this is nevertheless the dominant color; it is usually due to the quartz grains being coated and held together by a crust of earthy ferric oxide very much as in the Triassic sandstones of the Connecticut valley, which are deposits of undoubted land origin under a semiarid climate. Further, Goodchild points out that some of the red sandstones of Scotland are often full of desert sand grains, and are highly false-bedded in places, like an old desert sand-dune.

In the Old Red there are no thick, evenly bedded limestones, and the amount of carbonate of lime present at certain horizons is not greater than that found in undoubted continental deposits. The Old Red abounds in land plants and most of the fishes are of unmistakable fresh-water types. Of true marine animals there are none, though the small sharks and the small to gigantic eurypterids may have migrated from such waters. With none of these, however, are associated marine shells, and on the other hand it is well known that a few kinds of sharks are living to-day in fresh waters. If sharks adapt themselves to fresh waters now, why may they not have done so in the past? Therefore, the only evidence against the view that the Old Red is of continental origin is that of the eurypterids.

Eurypterids (Fig. 423) are locally abundant in the lowest beds, one even attaining a length of 6 feet. Previous to the Old Red, all eurypterids occur in unmistakably marine or at least estuarine associations, but toward the close of the Silurian, both in Europe and America, they are nearly always restricted to brackish-water assemblages. After Silurian time none of these animals are found in normal marine associations, and the last occur in the Pennsylvanian, where they again appear either in brackish-water faunas or in association with land plants and with a complete absence of marine animals. It is therefore held, and justifiably so, that the later eurypterids traveled far up the estuaries and even into the fresh-water rivers either in search of food or more probably to spawn.

Mixed Marine and Fresh-water Faunas. — Wherever the Old Red land fishes are found associated with marine faunas, it is seen

that such mixtures have taken place near the shore lines of the Devonian epeiric and shelf seas. Therefore these occurrences may be cases of moribund fresh-water animals floated to the sea by the rivers, or they may be of species that have interchangeable marine and fresh-water habitats, as have many modern fishes, such as the salmon. Kayser, and more especially Walther, holds that the Old Red areas were lagoons of the sea in which the character of the water recurrently changed; for long intervals the sea was present in the lagoons, followed by equally long periods when it was out of them, or the rivers dried out before attaining the sea and then over the areas of the deltas were deposited irregularly variable sheets of desert deposits derived from the highlands.

We are reminded by the Old Red of the Teri region of southern India, where the wide coastal plain is covered by wandering dunes of carmine red sands nearly two hundred feet high, between which are beautiful dark blue lakes whose shores are decorated with palms. Here are forming thick red sandstones with typical dune-bedding, beside thin-banded red clays at the bottoms of the lakes. Not far away are being deposited marine limestones and sandstones decidedly rich in beautiful pearl shells and snails, which gradually pass into coral reefs with their teeming life. Just as these sands of Teri are coated with a thin layer of iron oxide, so were those of the Old Red, and we cannot escape the conviction that both were caused by identical semiarid climatic conditions. (Walther.)

Plants and the Climate. — In the Devonian there is much evidence of land plants, but it is not until the Middle Devonian that we can speak of floras, for in the Lower Devonian these fossils are still very scarce. Although this is not the proper place to discuss the origin of the land plants, which will be taken up in Chapter XLII, it may be said here that paleobotanists hold that the Devonian or oldest floras probably originated in the marsh areas of the rivers and tidal flats along the seashores, and that they seemingly extracted much of their carbon dioxide from the water through their roots and in least degree from the air. At first there was little woody structure in them and therefore the plants were delicate and small, with thin, slender, or spiny leaves. Their evolution, however, was rapid, for in the Upper Devonian there was a considerably diversified flora, forming the oldest or first forest, in which flourished fern-like plants, rushes, tall ground pines (lycopods), and primitive evergreens with woody trunks nearly 2 feet in diameter. Drifted logs of these trees are often found in the marine deposits of Upper Devonian time. As the dominant plants were fern-like forms, this flora of the Upper Devonian has been called, after one of them, the Archæopteris flora, and the time, the *Age of Archæop-*

teris (see Fig. 424). As the flora in its broader aspect was not very unlike that of Pennsylvanian time, the detailed description of it is deferred to Chapter XLII. The Devonian forests, however, were devoid of all insects. One of the most remarkable facts in connection with this flora was its wide distribution and uniform character throughout eastern North America and into the Arctic region, Spitzbergen, and northwestern Europe, indicating equable climates and the complete union of North America and Europe across Greenland, Spitzbergen, Norway, and Great Britain. It is also probable that this region was the place where the first forests had their origin. None of the trees show annual rings of growth attesting to seasonal changes due to a varying climate or to prolonged drought and it is therefore held that the general climate of this time was uniformly warm though arid, the known forests being localized in wet places along the valleys and in the swamp areas. That the climate was warm is further shown in the wide distribution of the reef corals of the seas, which extended even into Arctic regions, but that the air was more or less arid is proved by the prevalence of the oxidized and red continental deposits of Eria.

Fig. 424. — Characteristic fern of Devonian time (*Archæopteris hibernica*). *A*, sterile branch, somewhat enlarged to show venation of leaves. *B*, fertile branch, about nat. size. *C*, spore cases, much enlarged. After Schimper and Schenk.

It is probable that the great Middle Devonian submergence of the continents described on page 701 had much to do with the development and spreading of this flora through the production of moist local climates. In other words, insular climates were locally developed in the otherwise general arid condition.

Thin coal beds of very local distribution are occasionally observed in the Old Red continental deposits, but these, as a rule, are of no commercial value; to the scientist, however, they indicate that swampy areas abounding in plants occurred where the coals are found. On Bear Island, to the north of Norway, are found beds of good bituminous coal sometimes 3.5 feet in depth.

Origin of Devonian Fishes

A general description of fishes is given in Chapter XXXVII, along with a detailed account of the various kinds found in the Devonian.

It is probable that the line of fish-like animals arose in some marine invertebrate ancestor, and it is apparently also true that the ancestral half-vertebrates have always lived in the sea as they do to-day, and that they probably were like the worm-like hemichordates described on page 691. It also seems probable that the vertebrate evolution remained in the sea up to at least the lancelet stage, for these animals are wholly marine in habitat. The further early vertebrate steps in evolution are unknown.

Geologic Record. — The oldest known fishes are the ostracoderms found in the Middle Ordovician of Colorado, South Dakota, and Wyoming (like Fig. 407). If the students of fossil fishes are correct in their conclusion that these animals had shark ancestors, then we are forced to add that the latter had their origin still earlier, and possibly as early as the oldest Cambrian. The geologic record shows clearly that the higher or more recent sharks have always been essentially marine animals, but that a few of them have adapted themselves to fresh waters is well known. However, the Old Red has many small sharks of undoubted fresh-water habitat, and their presence here takes on added significance when we remember that the Ordovician ostracoderms are also thought to have been fresh-water animals. It would seem, therefore, that the ancestors of the small ancient sharks lived in the sea and invaded the fresh waters, where they evolved into the spinous sharks; unfortunately, however, there are as yet no connecting fossils to bear out these surmises.

The spinous sharks were by no means the dominant fishes of the Old Red, nor were the ostracoderms. The majority of the fishes of that time were lung-fishes and ganoids, animals that were then more or less well adapted to double breathing, that is, had not only functional gills as have all fishes, but, in addition, lungs. We therefore see, further, that there must have been fresh-water fishes in the Ordovician and that they had evolved into the lung-fishes of the Silurian and Devonian. In other words, it appears to be a safe inference that the fresh-water fishes of the Devonian consisted of spinous sharks, ostracoderms, lung-fishes, and ganoids. Hence, the most fundamental evolution among the fishes had taken place previous to the Devonian, and the vista in the Ordovician shows that the greater part of it had occurred before the middle of that period.

Ancestors of Fishes. — Representatives of all of the probable vertebrate ancestors, whether invertebrates, half-vertebrates, or primitive vertebrates, up to the lancelet stage, are now living in the sea. To this may be added the further fact that all of these possible ancestral stocks are inhabitants of the shallow seas, and that the lancelets live just off the shores of the warmer waters.

As the marine lancelets represent more nearly than any other living type the probable progenitors of the higher vertebrates (Fig. 412), it seems safe to assume that the subsequent evolution up to the direct ancestors of the spinous sharks also took place in the shallow-water seas, for we find their spines in marine strata of the early Silurian. When the seas spread over the land, the primitive fishes occupied their widened habitat, and when the continents emerged, some of them were probably retained in the relic seas. In this connection, it should be remembered that there were three submergences of North America during the Paleozoic and previous to the appearance of the ostracoderms in the Middle Ordovician. Thus caught in the relic seas, the environment of the ancestors of the spinous sharks was bound to be gradually changed into one of fresh water, and even to dry land under the arid climates prevalent at that time. There was thus set up a struggle for existence which must have been fierce, bringing on stimuli which it is thought eventually resulted in the production of air-breathing animals. This latter aspect is discussed further on in the chapter.*

Food of Devonian Fresh-water Fishes. — Among living fishes some feed exclusively on plants, some on plants and animals alike, some exclusively on animals, and others on the mud in which minute plants and animals occur. The majority of fishes, however, feed on other fishes, without much regard to species, devouring their own young as readily as those of any other kind. Teeth with blunt tips usually serve for crushing shells; teeth with serrated edges often signify plant-feeding forms; while strong incisors may indicate the choice of snails and crabs as food. In general, the sharper the teeth and the larger the mouth, the more distinctly a species is a fish-eater. Small-mouthed fishes are apt to be plant- or mud-eaters. Fishes grow as long as they live and their size depends upon their ancestry plus the amount of food procurable: the length of life is variable; some exist many years, others are short-lived, and some appear to be annuals. (Jordan.)

* A very instructive paper on this subject, by Professor Chamberlin, is entitled "On the habitat of the early vertebrates" (Jour. Geol., Vol. 8, 1900, pp. 400–412).

From the living lung-fishes we learn that certain forms (*Lepidosiren*) inhabit muddy streams and marshes, where they feed on plants. Others feed on worms, insects, shellfish, crustaceans, and frogs. The lung-fishes eat voraciously during the rainy season, storing up great quantities of fat between the muscles. During the dry season they cease to feed and are sustained by this body fat until the water returns.

In the fresh-water deposits of Devonian time there is not as yet known a single definitely determined water-living plant, nor invertebrates of any kind other than bivalves (see Fig. 425) and myriapods. The ultimate basis of fish food, however, must have been water plants and algæ. There was probably also an abundance of earthworms present though their bodies were too soft for preservation as fossils. The sluggish bottom-living Devonian fishes were, then, dependent upon water plants, and upon these fishes subsisted the more active carnivorous forms. That food was still scarce in the streams and lakes of Devonian time is attested by the average small size of these ancient fishes, few of which exceeded 6 inches in length. In the marine waters where food was plentiful, the average length of fishes was far greater, and one at least of the Arthrodira attained to 20 feet. It is probably because of the abundance of food in the seas and oceans that we see so many different stocks of land fishes returning and adapting themselves to these more favorable habitats.

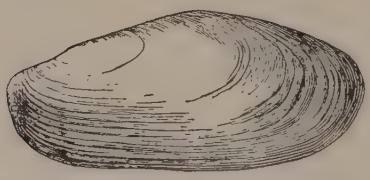


Fig. 425. — Probable fresh-water Devonian bivalve (*Amnigenia catskillensis*), from New York. × ½. After Hall.

Origin of Double Breathing in Fishes

Breathing Organs of Marine Animals. — A survey of typical marine animals reveals many and diverse methods for the extraction of the free oxygen from the water, but whatever the kind of breathing organ, it is always of the same fundamental type, a localized organ or organs having delicate canals with very thin membranes in which the blood circulates, bringing the red corpuscles into almost direct contact with the surrounding water. These red corpuscles have decided affinity for oxygen, which they extract from the water and carry through the circulation of the blood to all parts of the animal's body. Nowhere in the sea has any animal an additional organ for the extraction of oxygen directly

from the air, excepting in such stocks as are known to have had land-living ancestors.

Evolution of Lungs. — There is in all fishes above the sharks a structure known as the air or swimming bladder, which is structurally a sac-like outgrowth, single or paired, of the alimentary canal. Two exceptions to this rule are found, first, in those fishes which, because they inhabit swiftly running waters, have developed quick darting movements and have therefore lost the air bladder; and, second, in the flounders that lie upon the sea bottom awaiting their prey.

The principal function of this structure in living fishes is that of a hydrostatic organ, to give buoyancy to the animals, and it is controlled by muscles in such a way as to permit its possessor to remain at any desired level in the water. The air bladder is the homologue of the lungs of the terrestrial vertebrates, and is utilized by the so-called lung-fishes, and to a limited extent by other relic fishes (*Amia*, *Lepidosteus*, *Polypterus*) as a respiratory organ supplementary to the gills.

The great range of modification of this structure shows it to be of extremely ancient origin, and its incipient condition is probably shown by a pair of pouch-like outgrowths of the pharynx, or throat cavity, in the sharks. Stagnation of the water and a loss of free oxygen would bring the fishes to the surface to gulp down air, like goldfishes in a neglected aquarium, and such pouches, if supplied with blood-vessels, would serve in a very rudimentary way to aid in aërating the blood. A premium placed upon such structures would stimulate their development to the condition seen in the modern lung-fishes. Almost simultaneously the secondary function of buoyancy would be acquired, and in those fishes in which the power to breathe the atmosphere was unnecessary, this would become the main purpose of the organ. In many teleosts, or modern bony fishes, the connection between the air bladder and throat has been lost, and with it the possibility of respiratory use. On the other hand, permanent adaptation to land life among vertebrates could only come about through the perfection of the breathing function on the part of this ancient structure. (Lull.)

Origin of Lungs in Animals Living in Temporary Bodies of Water. — Animals originating and living in permanent bodies of water, and especially in the ocean, have no need to breathe the air, and it is, therefore, held that the stimulus for such an alteration could have taken place only where the water periodically failed the animals. Such places are very few, practically only the strand areas and the fresh waters of the land under a more or less arid climate.

Along the strand-line the breathing of air has been developed but seldom, apparently only by a few groups of gastropods, crustaceans (land crabs), insects, and scorpions. No fish permanently breathing air is known to inhabit the region between low and high tides, though several kinds live here for a time in search of food. In all of these cases there are developed in the gills secondary spongy structures that absorb, while moist, the oxygen of the atmosphere. However, these secondary gill structures do not correspond to the homologues of the lungs. On the other hand, in none of the marine deltas of the present does one find the climatic conditions necessary to force fishes to develop into lung-fishes, nor do they occur in the areas of the strand-lines or in the courses of the permanent rivers. Nowhere is there in these places a transition zone forcing the water-living fishes to adapt themselves to the dry land.

It is well known that large bodies of sea water have been captured from the ocean (for example, Caspian, Baikal, Nicaragua), and this probably often occurred during the Paleozoic emergences. Just as we have arid regions to-day, so it appears that similar land climates existed during much of Paleozoic time. Under such climates, bodies of water come and go according to the season of rain and drought, and hence various methods are resorted to by the animals to maintain their kind or themselves over the period of drought. During the arid season the struggle for existence is severe, not only because of the abnormal crowding of the individuals into constantly diminishing spaces and the reduction in the amount of available food, but even more so because of the increasingly saline and bitter character of the water. It is thought that under the stimulus of these violent changes the gill-breathing fishes first adapted themselves to burrowing in the sand. Thus protected in water and mud holes there was for a time moisture to pass over the gills, but under such environments life was very precarious and in the struggle most of the individuals were destroyed. After innumerable failures in their efforts to gulp the air into the pharynx, efforts lasting through long geologic time, the lung-fishes were gradually developed and perfected, their first appearance being in late Silurian time.

Homes of Living Lung-fishes. — The conditions pictured here are not fanciful, but are based on the actual habitats of modern Dipnoi, animals that not only maintain life in the foulest of waters, but in times of drought burrow and even encase themselves in a mud cocoon with an air opening at the top, breathe through the mouth after closing the gills, and thus live for months at a time out of water until the drought is over and the rivers return. In Africa the natives often dig such lung-fishes out of the mud for food.

Highest Mentality among Land-living Vertebrates. — Air breathing, once established among the fishes, has resulted in the land vertebrates attaining to the highest mechanical and mental perfection, an evolution necessitated by adaptation to a wide range of environmental conditions as compared with the relative uniformity of the sea. The greatest mentality in the sea has been repeatedly derived from the continents, in that many stocks of land vertebrates have adapted themselves to the sea because of the ease with which they can there prey upon the less alert and intelligent. Such adapted stocks in the course of geologic time grow larger and larger, as, for instance, the whales of to-day, whose origin goes back to the Eocene. Out of such stocks, however, comes no higher mentality. They represent an adaptation in the wrong direction, that is, to an easier life, for the highest mentality has been developed only on the land where the struggle for existence is greatest because of the constant necessity of adaptation to changing environment. Organic supremacy is attained only through constant vigilance.

CHAPTER XL

CARBONIFEROUS OF OLDER GEOLOGISTS, AND THE MISSISSIPPIAN PERIOD

History of the Term Carboniferous. — The geologists of more than a century ago classified the periods of geologic time on the basis of kinds of deposits, as, for example, the Old Red sandstone, the New Red sandstone, the oolitic rocks of Oolite time (Jurassic), the chalk of the Cretaceous, and the coals of the Carboniferous. Such a classification, based on the kinds of rocks, they believed was a natural one, and they also thought that the same kind of materials was deposited everywhere at the same time. This petrologic classification, however, because of its unreliability, has long since been abandoned for the more dependable one based on the contained fossils.

In western Europe, where Geology had its inception, the coal-bearing strata are of wide occurrence, and as long ago as 1808 Omalius used the term " bituminous terraine " for the coal deposits of Belgium. Later the English geologist Conybeare (1821) called these formations the *Carboniferous System* and this term came to be applied to all the strata above the Old Red and beneath the New Red, or Triassic. The term Carboniferous system is still widely used in Europe and embraces the lower series, the Carboniferous or Mountain Limestone, and the upper coal-bearing series, the Coal Measures (William Smith, 1817). The lower limestone series, while of wide distribution, was shown by Murchison and Sedgwick (about 1836) not to be of this rock everywhere, but even in England to be locally replaced by sandy shales that are known as Culm Measures. (The word " Culm " originated in South Wales and refers to a natural slack from anthracitic coal, the origin of this slack being due to the crushing of the coal beds during the process of mountain making. Arber.) This latter term they applied to the lower series when composed of sandy mudstones, and even to-day throughout western Europe Culm (or Kulm) is much in use. Culm Measures and Mountain Limestone are, therefore, regarded as deposits of one time, but laid down under different physical conditions.

Marked Variability of Carboniferous Formations. — The Carboniferous deposits of western Europe are very variable in character, and the time of their deposition is also different in the various areas, indicating that these small basins of deposits were bordered by lands with differing physiography and character of rocks. In addition, there was a deforming movement taking place, for east of the Rhine valley the Coal Measures rest unconformably upon the Culm series. In eastern Europe and Russia the basins of deposits were far larger in areal extent. Under these varying conditions it is to be expected that the thickness of the deposits would also be variable, and in places it attains to 13,000 feet and more.

Divisions of the European Carboniferous. — The European Carboniferous is now separated into two primary divisions, the lower one of which is called *Lower Carboniferous* or Culm (sometimes Dinantian, from the city of Dinant, Belgium), and the upper one, *Coal Measures*. The French geologists further divide the Lower Carboniferous into two series, the lower being their Tournaician (Tournai, Belgium), and the upper their Viséan (Visé, Belgium).

The Coal Measures formation is again divided into two series, the earlier half, or Middle Carboniferous, being widely known as the Westphalian (from the province of Westphalia, Germany) when coal-bearing, and Moscovian (from Moscow) when of normal marine deposits. The upper series, or Upper Carboniferous, is called Stéphanian (St.-Étienne, France) when it has coal deposits, and Uralian (Ural Mountains) when of marine character. Kayser adds a third series, the Namurian (Namur, Belgium), which is referred to the base of the Middle Carboniferous.

The above succession expressed in tabular form is as follows:

Carboniferous	Coal Measures or Upper Carboniferous	Stéphanian or Uralian
		Westphalian or Moscovian
		Namurian
	Lower Carboniferous, Mountain Limestone, Culm, or Dinantian	Viséan
		Tournaician

History of the Term Permian. — In Great Britain occur other higher strata that were at first confused with the Carboniferous, and in Germany certain equivalent red beds were erroneously included in the younger Triassic series. These incorrect references of the beds did not become apparent until after 1841, when Murchison proposed the term *Permian* for a thick series of marine strata that lay above the marine Carboniferous and beneath the continental red Triassic along the western flank of the Ural Mountains in the Government of Perm, Russia. In Germany the equivalent of these deposits was long known as the copper-bearing rocks; in that country the Permian has a lower red, conglomeritic and sandy series of continental origin, known as the *Rotliegende* (lower red), and an

upper shaly and calcareous marine member known as the *Zechstein* (a miners' term, of unknown origin but possibly from *zähe*, meaning *tough*). Because of this two-fold development, the series was called the *Dyas* (meaning two-fold) or Dyassic period, but as this name was of later origin than Murchison's term it could not displace Permian, though it is still used locally. In northern Germany the Permian closes with salt beds upward of 3400 feet thick (see page 674).

Carboniferous of Europe and America compared. — The geologists of Europe now recognize but two systems of rocks above the Devonian and beneath the Triassic, namely, the Carboniferous and Permian systems. It will be shown, however, that their Lower Carboniferous is also clearly distinguishable as an independent system or period. There are, therefore, embraced in the Carboniferous at least three periods, (1) Lower Carboniferous, (2) Upper Carboniferous, and (3) Permian.

In America these three periods are also developed, but the Permian is far less extensive than that of Europe and Asia. On the other hand, the Lower Carboniferous is much better recorded in the Mississippi valley than in any part of Europe, and on the diastrophic principle of classification the rocks are not only clearly separable from the overlying Coal Measures but apparently can be divided into two systems, as will be explained farther on in this chapter. In regard to the Permian of America, its strata are almost everywhere inseparably connected by transition beds with the Coal Measures and therefore both will be described in this book as if they were one period. It is thus apparent that the classification of Carboniferous formations into systems is markedly different in America from that of Europe.

The Productus Seas.— The seas of the three Carboniferous periods the world over were characterized by an abundance and great variety of brachiopods of the genus *Productus* (see Pl. 23), and have hence been called the *Productus seas*. These shells are always common, and as they are of large size, they are the most conspicuous and easily secured fossils of the Carboniferous marine formations. Further, as the genus died out during Permian time, they are the best guide fossils to the Carboniferous strata. It is true that this stock arose in the Middle Devonian, but even though the forms of the ancestral genus *Productella* were not rare in the Upper Devonian, they were then neither large nor common enough to dominate the marine faunas as they did in the Carboniferous throughout the world.

Development of the Carboniferous Succession in America. — Early in the thirties of the past century the term Carboniferous was more or less correctly applied to the coal-bearing strata in America. However, it was then and for a long time afterward also erroneously applied to older black shale deposits and much labor was spent upon such Ordovician strata along the Hudson River and elsewhere in a vain endeavor to find coal in them, the belief prevailing that because these formations were black they must have coal under the ground. The surprise of the prospectors for coal was great when the geologists of the New York survey in 1838-1842 told them that if they were to find coal they must turn about and dig upward, in other words, that coal could not be found in these ancient rocks, but only in much younger strata, none of which now occur in New York State, since they have been eroded away.

We need not go deeply into the history of how the American succession of Carboniferous strata was determined, but will add that the Lower Carboniferous has long been called *Subcarboniferous* (Owen, 1852). A part of these strata in Ohio was also known as the *Waverly sandstone series* (Mather, 1838), but not until 1869 was a geographic name proposed to embrace all of the Lower Carboniferous limestones. This was the *Mississippi Group* of Alexander Winchell, who applied the term to the Lower "Carboniferous Limestones of the United States which are so largely developed in the valley of the Mississippi River." In 1891, Professor H. S. Williams revived this term as the *Mississippian series*, defining it as "that series of rocks, prevailingly calcareous, which occupies the interval between the Devonian system and the Coal Measures, and is typically developed in the states forming the upper part of the valley of the Mississippi River, viz., Missouri, Illinois, and Iowa." This name is now in general use as a period term.

The sequence of all of the Carboniferous formations was first worked out in the Mississippi valley, and not in Pennsylvania, because in that state, although the coal-bearing series (Coal Measures) is so well developed, the Lower Carboniferous strata are almost devoid of fossils. The succession of the Coal Measures, on the other hand, was first determined in Pennsylvania by Henry D. Rogers for the United States Government in 1838, and to this sequence Williams in 1891 applied the term *Pennsylvanian series* as a period name, and this is also in general use.

Permian in America. — It has always been difficult to appreciate fully the differences in the marine faunas of the original Permian when compared with those of the Coal Measures of Europe, because

so many of the fossils are very similar or alike. No one now doubts the presence in America of strata equivalent to a part of the Permian of Russia, but as there is in most American areas a complete transition between the Coal Measures and the beds regarded as of Permian age, there is not complete accord among geologists as to where the line between the two systems is to be drawn. Strata of Permian age were first identified by Meek in Kansas in 1857, but there have always been geologists who doubt this correlation. It is not one of easy adjustment because these marine beds gradually go over into red ones that are almost devoid of fossils. Many geologists, on the other hand, avoid the difficulty by calling these beds *Permo-Carboniferous*, a term that truly indicates their position, for they are transitional between the Carboniferous and the Permian. In this book they will be classified, however, as of Permian time, but the formations will be combined with those of the Coal Measures as if representing but a single period, for the reason that there is no break of marked importance in the sedimentation between these two periods in America. In other words, there was but a single sea transgression, for the flooding of the continent continued throughout Pennsylvanian and into early Permian time. Then the seas began to vanish and the North American continent emerged, in the throes of the Appalachian Revolution. This matter will be treated of in more detail later on.

The divisions of the Carboniferous of North America are as follows:

Permo-Pennsylvanian periods

Permian	In Texas	Capitan of Trans-Pecos Texas				
		Double Mountain				
		Clear Fork				
		Wichita, Wreford of Kansas				
	In central	Cisco, Neosho of Kansas	In Pennsylvania	Dunkard	Autunian and Cuseler	In Europe
Pennsylvanian		Canyon		Monongahela	Stéphanian or Uralian	
		Strawn		Conemaugh		
		Millsap		Allegheny	Westphalian or Moscovian	
		Bend		Pottsville		

Break

Mississippian period

Tennesseian	Kaskaskia		Chester (Mauch Chunk)
	Ste. Genevieve		
	St. Louis		Meramec
	Spergen		
	Warsaw		

Break

Waverlian	Keokuk	Osage	Madison of the western or Cordilleran sea
	Burlington		
	Fern Glen		
	Kinderhook-Pocono		
	Chattanooga		

Plate 19. — Mississippian paleogeography.

Mississippian Period

The geologic record of Mississippian time in North America is markedly different from that of the Pennsylvanian, for the former is one of the sea alone, while in the latter in the eastern half of the continent there is an alternation of the sediments of marine floodings with accumulations of coal beds in vast more or less fresh-water swamps. In other words, the Mississippian is a recurrence of Devonian conditions, while the Pennsylvanian formations alternate between those of the sea and land.

Waverlian Seas. — The Devonian period closed with marked retreat of the seas in North America and it appears that all parts of the continent were emergent. How long this complete emergence lasted is not known. The submergence of Waverlian time began first in the Gulf States and along the western side of the Cincinnati uplift, the water depositing nearly everywhere a fine black mud almost devoid of fossils (Chattanooga formation). At this early stage of the inundation the seas were small in extent but in Middle Kinderhook time the waterways were greatly expanded. The most striking change of this time, however, was the reappearance of the *Cordilleran sea*, depositing far and wide throughout the Rocky Mountains a great mass of limestones, known as the Madison limestone, that in places attains to a thickness of 1600 feet. It is exceedingly massive and where upturned the streams have cut in many places deep and picturesque canyons through it. This Cordilleran sea is known as far north as Alberta (Lower Banff shale and limestone with a thickness of 2300 feet) and it is probable that it extended into the Arctic Ocean. That it connected with the Central Interior sea is proved by identical species in both; in fact, more than one third of the Cordilleran forms also occur in the Central Interior sea. The Cordilleran sea, then, remained throughout Waverlian time and seemingly vanished completely at the close of this epoch. During the maximum submergence of Waverlian time about 26 per cent of North America was under the sea (see Pl. 19, Fig. A).

The *northern Appalachian basin* existed throughout Waverlian time east and north of the Cincinnati uplift in the states of Ohio, Michigan, and Pennsylvania, and it is from this area (Waverly, Ohio) that the epoch name is derived. It was a shallow basin with coarse deposits throughout—sandstones and shales, with some conglomerates and but little calcareous material. The life of this basin also had its own impress, but as there were many species common

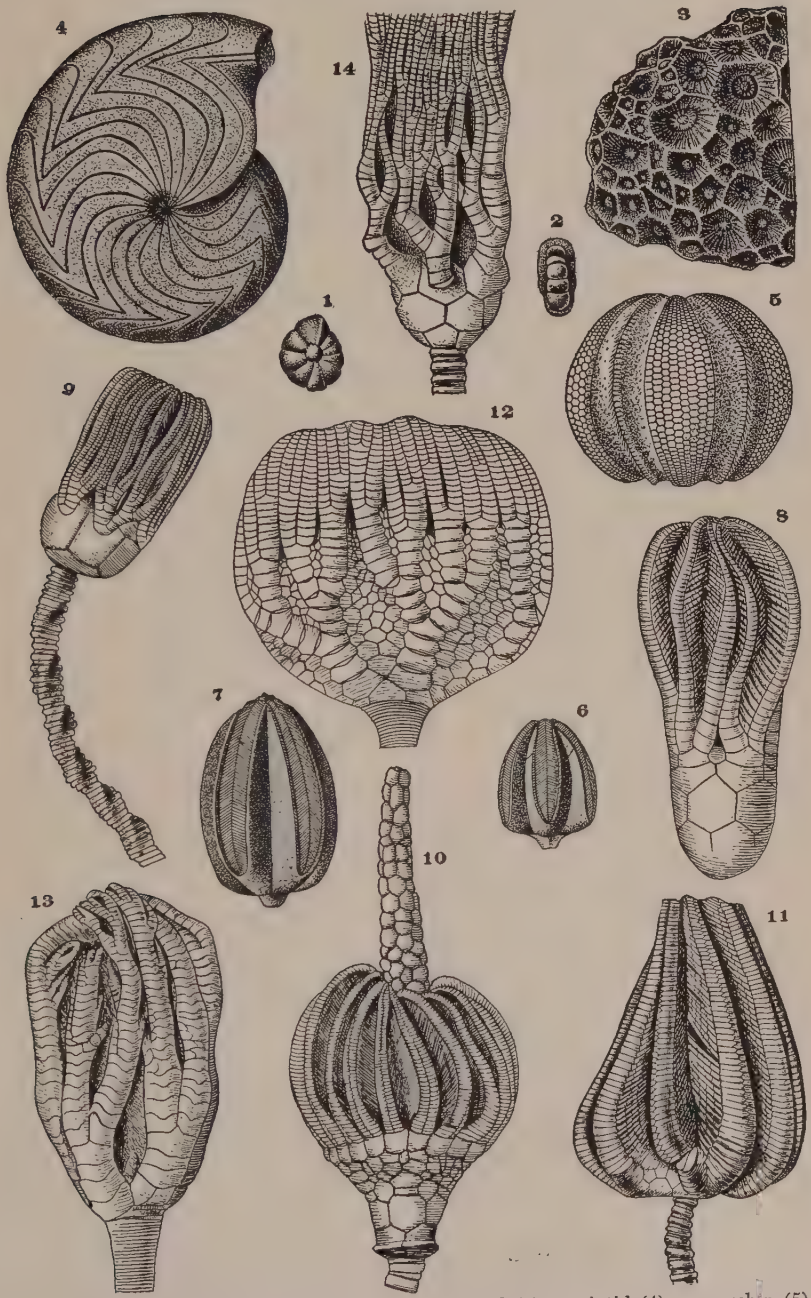


Plate 20. — Mississippian Protozoa (1, 2), reef-coral (3), goniatid (4), sea-urchin (5), blastids (6, 7), and crinids (8–14, 9–11 camerate).
See Appendix B.

to it and the Central Interior sea it is plain that they were connected.

In the *Central Interior sea* the invasion began with black mud deposits (Chattanooga) and for a long time the sediments were of this character, with local sand accumulations. During Kinderhook time the waters west of the Cincinnati uplift clarified and then for a long time remained clear, depositing over great areas the later Kinderhook and Burlington crinidal limestones. The entire thickness of Waverlian deposits at Burlington, Iowa, is about 300 feet, but the series thickens considerably to the south.

In Middle Waverlian times the life was most diversified, and the sea was filled with an abundance of crinids in great variety, a richness of development never again attained by this class of radiate animals (Pl. 20). They were at first delicate forms, becoming larger, thicker plated, coarser, and more ornate with the progress of time. About the city of Burlington alone nearly four hundred species have been found and through the quarrying of the limestones these fine fossils became readily accessible, thus stimulating several collectors living in the city to turn to natural history and geology as a vocation. Other kinds of fossils were also abundant, as, for instance, brachiopods (*Productus*, *Spirifer*), bryozoans, and cup corals, but none attained the profusion of the crinids. That reef-building corals were not present in this warm and clear sea is strange, since reefs were made at this time in Europe. Large sharks were becoming more and more plentiful, for their flat, crushing teeth (cestracionts and cochliodonts, described on page 684) and large fin spines are often abundant, and especially so at the close of this epoch (Keokuk). Among cephalopods, the nautilids were no longer so prevalent as they were in earlier time but they were now more ornate, with spiral ridges and nodes, while the central part of the spiral was more often open. Their descendants, the goniatites (Pl. 20, Fig. 4), were more common than in the Devonian, but this statement applies rather to the European seas than to the Central Interior sea. Trilobites were almost gone. The carnivorous or aggressive life of the Waverlian sea was therefore dominated by the pavement-toothed sharks. It is interesting to note here that the life of this sea was much like that of western Europe, seen to best advantage in the equivalent strata of Belgium (Tournaician), indicating that these waters were in connection with each other.

In the *Acadian area* there was another sea of this time, consisting of narrow connected troughs between mountain ranges made during

the Shickshockian Disturbance (Pl. 19, Fig. A). The wider of these seaways deposited conglomerates, sands, much mud, thin zones of dolomites, and great quantities of gypsum. At the top the series commonly has extensive sheets of igneous rocks. These Acadian deposits are known as the *Windsor series* and at times are rich in fossils. The fauna is a distinct one and has no known relationship to those of other seas, either in America or Europe. The thickness of the rocks is estimated at from 2000 to 5000 feet, and the formations occur in New Brunswick, Nova Scotia, and southwestern Newfoundland. In some troughs occur deposits which seem to be entirely of fresh-water origin, with but few fossils (Horton and Bonaventure formations).

Land Life of Waverlian Time. — Of land life little is known other than plants, and most of these are preserved in the Pocono deposits of gray sandstones and conglomerates, 400 to 1400 feet thick, of the Appalachian trough, which are partly of marine but mainly of fresh-water origin. The plants are so like those of the Pennsylvanian that a description of them is deferred to Chapter XLII. Here we also find the oldest American coal beds, thin accumulations of little commercial value but prophetic of the thicker beds occurring in later formations. However, coal was forming early in Waverlian time in other and widely separated

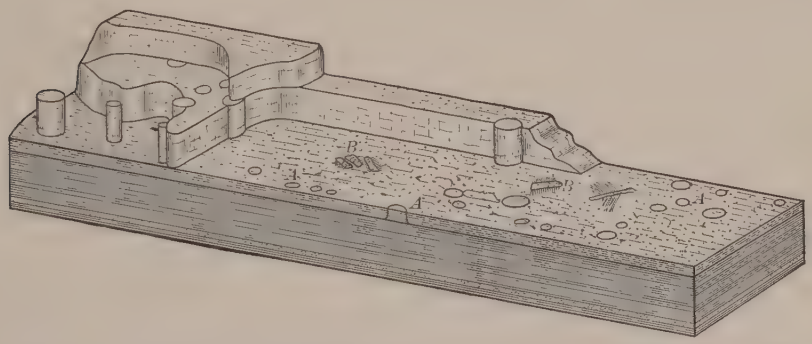


Fig. 426. — Ground plan to scale ($\frac{1}{67}$) to show twenty-seven vertical trees (*Lepidodendron*) in Mississippian strata at Horton Bluff, Nova Scotia. *A*, trunks; *B*, roots. Area sketched 22 × 6 feet. Drawn by W. A. Bell.

places, as in arctic Alaska (Capes Lisburne and Thompson), southern Siberia, and Scotland; and later thin coal beds were accumulating in western Europe in some of the Culm deposits. At Cape Lisburne the coals are non-coking and semi-bituminous, in beds up to 4 feet thick of clean coal, which is now mined.

In the Horton formation of the Evangeline country, Nova Scotia, many land plants are found and here occur also several zones with the bases of small trees (*Lepidodendron*, see page 769) standing vertically, their roots preserved in the ancient soil of the forests. On a surface 120 by 15 feet, Walter A. Bell in 1914 counted ninety-six vertical trunks embedded in a dark greenish, sandy-mud matrix. A part of this layer is illustrated in Fig. 426.

Fresh-water fishes are practically unknown in the American deposits of the Waverlian period, but those of Europe indicate a marked decline of the stocks seen in Devonian time. Of land vertebrates also the record is almost a blank, and the little that is known will be presented at the close of this chapter.

Close of Waverlian Time. — The Waverlian submergence was at its height late in Burlington time and the emergent period continued during Keokuk time. The Central Interior sea again became muddy in the north, where shales and sandy shales dominate, and even the limestones farther south are less pure than those of earlier time. The greatest changes, however, were in the Cordilleran sea, which appears to have been completely withdrawn and did not reappear for a long interval. As the emergence of the continent seems to have been complete, the evidence is in favor of dividing the Mississippian into two periods instead of one. Ulrich was the first to point out this general emergence and to apply to the subsequent submergence the period term *Tennesseian*.

Tennesseian Seas. — Tennesseian time in North America was one of much emergence, for the only marine deposits known to be of this epoch are those of the Central Interior sea and the southern Appalachian and Cordilleran troughs. The whole of the Nashville dome, however, was submerged (see Pl. 19, Fig. B). Nowhere are there more than 1100 to 1800 feet of sediments, most of which in the center of the area are limestones and oolites. On the flanks and especially along southern Appalachia, however, there are sandy or calcareous shales that in the northeast are, in the main, of continental origin, being soft, red, sandy shales devoid of fossils (Mauch Chunk, at Pottsville, Pennsylvania, 3000 feet thick, thinning to 600 feet in western Pennsylvania and 40 feet in West Virginia). During the Tennesseian it appears that at no time was more than 12 per cent of North America submerged, while the average for the epoch may have been about 8 per cent. Finally, all the waters were withdrawn except in the Quachita geosyncline south of Ozarkia, since in Arkansas there appear to be strata that are transitional into the next or Pennsylvanian period.

Life of Tennesseian Time. — The marine life of Tennesseian time differs in many ways from that of the Waverlian, but as it is largely a direct outgrowth of the latter it naturally cannot vary greatly. One of the noticeable features of this life is a dwarf fauna of more than seventy species which reappears at least four times but is always connected with the same physical environment, shallow-water oolite deposits. Abundantly associated with this fauna is a single species of Foraminifera, a division of the Protozoa (Pl. 20, Figs. 1, 2), which will be described in a later chapter. This life assemblage (biota) is known as the Spergen fauna because it is best developed in the Spergen formation of Indiana. The crinids were no longer so diversified as they were in the preceding epoch, but two other groups of echinoderms were far better developed. These were the blastids (*Pentremites*, Pl. 20, Figs. 6, 7) described elsewhere (page 658), which are the guide fossils to the marine deposits of this time, and in places are so common that geologists have called the beds the Pentremital limestone; and, associated with them, though far less common, the equally characteristic sea-urchins known as *Melonechinus* (the melon-like urchin, see Pl. 20, Fig. 5, and page 656). Bryozoa with a thick, screw-like axis (*Archimedes*) were also characteristic of this epoch and certain horizons filled with them have been called the Archimedes limestone. Pavement-toothed sharks like those of the previous epoch were still prevalent but were rapidly dying out and not of marked significance in later times. There were many kinds of cup corals, and one type of compound coral (*Axinura*, see Pl. 20, Fig. 3), which was especially characteristic of this epoch, formed small reefs.

Land Vertebrates. — Toward the close of Tennesseian time throughout the continental deposits of Pennsylvania known as the Mauch Chunk are seen the tracks of many kinds of amphibians, nearly all of which are still undescribed. Lea in 1849 collected a most interesting slab, a little over 5 feet long, with six successive series of foot impressions made by an amphibian (*Palæosauropus*) with a 13-inch stride. This slab is ripple-marked and has rain imprints, indicating a mud flat of land origin, over which the animal walked when the deposit was yet soft and wet. Another amphibian track has been found in Giles County, Virginia (*Dromopus*).

Quachita Disturbance Toward Close of Tennesseian Time. — In the southern Appalachian geosyncline of central Alabama there are more than 3000 feet of continental conglomerates and sandstones of earliest Pennsylvanian age. Farther west in the Quachita (pronounced wash′-e-tah) geosyncline of Arkansas, Oklahoma, and

Texas the marine and brackish-water sediments of the same period exceed 8000 feet, all of which coarse sedimentation indicates that southern Appalachia and Mexico (or the ancient land Columbia) had been in decided elevation during the latter part of Tennesseian time. It is these orogenic movements, followed by the Quachita interval of erosion and the resulting unconformities, that distinguish the Tennesseian from the Pennsylvanian. To emphasize this it is proposed to speak of these movements by the term *Quachita Disturbance*. Similar movements were of even greater extent throughout western Europe.

Petroleum. — Natural oil is obtained in the Mauch Chunk (Keener sand) of southeastern Ohio and West Virginia, and in the Pocono (Big Injun and Squaw sands) of southeastern Pennsylvania, southeastern Ohio, West Virginia, and eastern Kentucky. In this same area there are ten productive oil horizons above the Mauch Chunk and beneath the Pittsburgh coal bed; in other words, all are in Pennsylvanian sediments (four in the Pottsville, three in the Allegheny, and three in the Conemaugh).

Geological Map. — The surface exposures of the Carboniferous formations are shown on the Geological Map of North America at the end of this book.

CHAPTER XLI

PENNSYLVANIAN-PERMIAN PERIODS, THE TIME OF GREATEST COAL MAKING

Important Events in Europe

Two Cycles of Oceanic Spreading.—Nearly everywhere throughout Europe and Asia the Upper Carboniferous and Permian were marked by two cycles of oceanic spreading. While there may have been places where the seas were continuous from the one period into the other, this was not the rule. The stratigraphic succession, however, is very different in the various regions exposing the formations deposited in these seas, this being due to the marked deformation which went on for a very long time throughout Europe. In North America the period of mountain making began later, and, as the oscillatory nature of our Pennsylvanian seas was seemingly connected with the simultaneous deformation going on in Europe, it is well to present here a brief review of these latter movements.

Paleozoic Alps of Europe. — The Carboniferous period was a time of marked crustal movement, and was thus the cause of far-reaching changes in the distribution of land and sea. In central and western Europe, according to Kayser, the movements began shortly after the close of Culm time, continued with decreasing intensity throughout all of the Upper Carboniferous, and were renewed in the Permian. In the heart of Europe there arose a mighty chain of folded mountains, the *Paleozoic Alps of Europe*, whose stumps may be seen in the mature mountains of massive rocks in Germany, France, England, and Ireland to-day (see map, Fig. 427; their general aspect may be seen in Fig. 296). The western ranges extending from Ireland across Wales and southern England to the central plateau of France, Suess has named the *Armorican Mountains;* the eastern ranges extending from southern France across the Vosges and the Black Forest to the Thuringian Forest, the Harz, the Fichtelgebirge, Bohemia, and the Sudeten, and possibly even farther east, he calls the *Variscian Alps*. The folding of the Urals also began in later Carboniferous time and attained its climax in the Permian. Even in Armenia, central and

eastern Asia, and North America can be followed the traces of the mountain-making movements of this time (see Fig. 427).

Intrusives. — Hand in hand with these dislocations arose enormous masses of eruptive rocks, especially granite in stocks and bathyliths, accompanied by porphyries of various kinds. The granitic rocks of the Harz, the Thuringian Forest, the Erzgebirge of Saxony, the Vosges and other regions are of Carboniferous age. Outside of Germany the intrusions of granite (mainly laccolithic) and other eruptive rocks played a large rôle in the Carboniferous; for instance, in Brittany, Cornwall, Scotland, and southern Norway.

Fig. 427. — Stereographic map of the eastern hemisphere, after Penfield, showing the Paleozoic Alps of Europe and many other mountain ranges formed at the close of the Paleozoic. Mainly after Arldt.

Important Events in North America

Submergence in North America. — The geologic history of North America during Pennsylvanian time was one almost devoid of crustal movements other than local warpings and periodic small subsidences of the sea bottoms. It was a period of quiet, for nearly

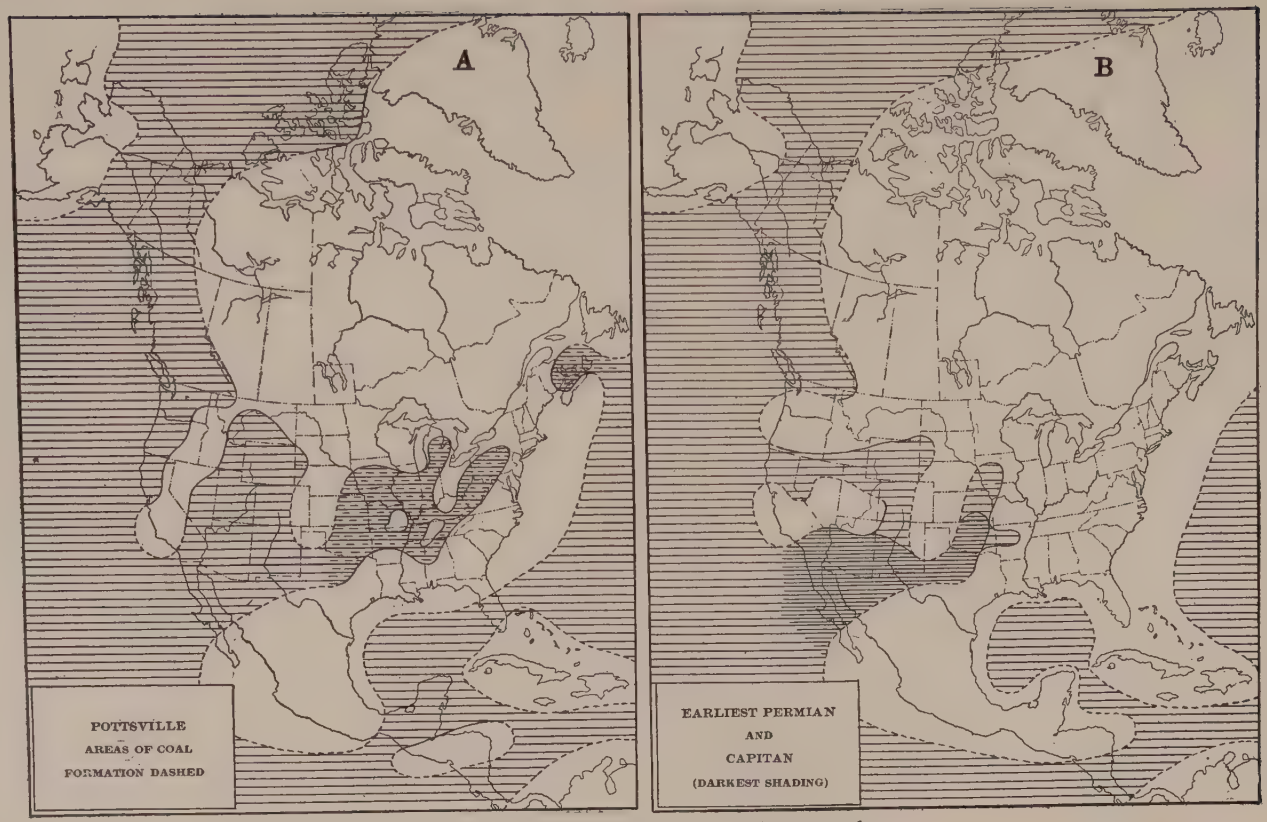


Plate 21. — Pennsylvanian-Permian paleogeography.

everywhere its deposits are distinguished from the older formations only by disconformity (see page 292). The seas quietly submerged the continent, coming mainly from the southwest and overlapping the land northward and eastward. The submergence was greatest in early Pennsylvanian time, when more than 30 per cent of North America was again under the sea. During the latter half of the Pennsylvanian, or possibly even earlier, the sea-level was oscillatory, and a retreat of the flood began late in this period, so that early in Permian time probably less than 5 per cent of the continent remained submerged. The waters continued to retreat rapidly and the sea was finally restricted more and more to the southwest of the United States (see Pl. 21).

While it appears that the greater part of the continent was not undergoing more than crustal warping in Pennsylvanian time, there seems to have been more decided unrest along the entire Pacific area from northern California into arctic Alaska. Here the limestones and calcareous shales of the Pennsylvanian and the early Permian are interbedded with much extrusive igneous material. The thickness in California is not less than 4600 feet, with a maximum of 10,000 feet, while in the Copper River region of Alaska it is nearly 7000 feet. The calcareous deposits often abound in fossils unrelated to those found elsewhere in North America; they are of the Pacific realm, while the life record of the eastern seas accords better with that of northern Europe, though in the main it is best regarded as constituting the North American province. Long after Pennsylvanian time had begun there was also decided crustal movement in western Colorado, Utah, and Arizona, and this is probably to be associated with the deformation of the Pacific border.

Sea of the Rocky Mountains Area. — In a previous paragraph it was stated that the Pennsylvanian seas in the area of the United States came in from the southwest, and as the nature of the sedimentary record of this submergence is very different in the east from that in the west, it must now be described. If we eliminate the Pacific province of indefinite marginal extension, it can be said that the life of these southern waters had throughout a fairly uniform fauna. However, in the area of the Rocky Mountains and the Great Plains, wherever Pennsylvanian formations (not including the Permian of the southern area) are known, they are of normal marine waters, and nowhere, in either Pennsylvanian or Permian strata, is there an alternation of this condition with that of coal making, such as is found in the central and eastern parts of the

country. In other words, in the western part of the United States there are no coal accumulations of this age, and the strata are nearly always limestones with calcareous shales (see Pl. 21).

Great Coal Deposits. — The most striking feature of the Pennsylvanian or Coal Measures in North America, Europe, and China is the fact that they contain the greatest known accumulations of coal. This has long been recognized and it led the older geologists to name the period the Coal Measures. It is true that much coal was laid down subsequently, and especially during the Cretaceous, but at no other time was so much valuable fuel deposited as during the Pennsylvanian. Because the nature of coal and its mode of formation are of such great importance to humanity, a special chapter will be devoted to them, and another one will describe the coal flora; in this chapter we shall present only a general statement of the main events and life characteristics of Coal Measures time.

Central Interior and Appalachian Seas. — In the Appalachian basin east of the Cincinnati uplift, and in the greater Central Interior sea to the west of this axis and extending into Nebraska, Kansas, Oklahoma, and Texas, the formations have more or less alternations of marine deposits with coal accumulations (see Pl. 21). It was in these areas, therefore, that the sea-level was oscillatory, and here the workable coals occur. In the Central Interior basin the coals are associated with more normal marine faunas and are interbedded with calcareous shales and limestones, this generalization applying in the main to the western side of the Cincinnati axis and less to the eastern side. In the Appalachian basin the mass of strata is not only thicker but also coarser, consisting, in general, of sandy shales and sandstones with the marine and calcareous zones inconspicuous or, locally, even absent, the marine zones vanishing eastward. Here also the coal accumulations are thicker, as the swamps were of greater areal extent and less often under the influence of the sea.

Character of Central Interior Deposits. — The essentially calcareous deposits of Pennsylvanian-Permian time in eastern Kansas have a united thickness of about 4600 feet, thinning into Nebraska and Iowa but thickening greatly southward, especially the lowest shale series with coal beds (Cherokee), which attains to 9000 feet in southern Oklahoma. Above lie about 3000 feet of younger Pennsylvanian-Permian deposits. In general, the series is an alternation of shale and sandstone, for the calcareous deposits of Kansas thin southward while the sandstones of Oklahoma vanish north-

ward. Furthermore, the fossiliferous marine condition of these beds in Kansas gradually vanishes more and more toward Oklahoma, and the greater part of the higher series changes into the widely known *red beds* of that state, Texas, and the southern Great Plains country (see Pl. 21, Fig. B). With the appearance of the red deposits not only do the marine fossils disappear, but tremendous amounts of gypsum occur in Oklahoma, which was the center of these sulphate-of-lime waters, and hence is often referred to as the "Gypsum State." On going farther south the amount of gypsum becomes less, the red beds yield very interesting amphibian and reptilian remains, and gradually the sediments change back again

Fig. 428. — Permian sandstone, 700 feet thick, Canyon de Chelly, between Del Muerto and Monument canyons, Arizona. Photograph from W. C. Mendenhall and H. E. Gregory.

in central and more especially in southwestern Texas (Rio Grande region with 8000 feet) to normal marine deposits with an abundance of invertebrate fossils.

From Oklahoma eastward into Arkansas the great thickness mentioned above is maintained, but here the red beds are practically absent. This tremendous amount of mud could not have been derived from small Ozarkia, but must have come from the southwest, or the land that has been called Columbia (see Figs. 428, 429). It is apparent, then, from the above paragraphs that the seas

retreated at first in the north, and that the last of the submergence vanished in the southwestern portion of the United States.

The red color and the presence of gypsum and salt are the striking phenomena of the late Pennsylvanian and Permian deposits of the southwestern United States and Europe. With the retreat of the Pennsylvanian seas and until their return in Europe in the Permian, the brackish- and fresh-water formations are as stated, and these conditions are interpreted as due to dry climates, evaporating the water, precipitating the salts, and oxidizing the sediments. It is also probable that the air was cool rather than warm, for at

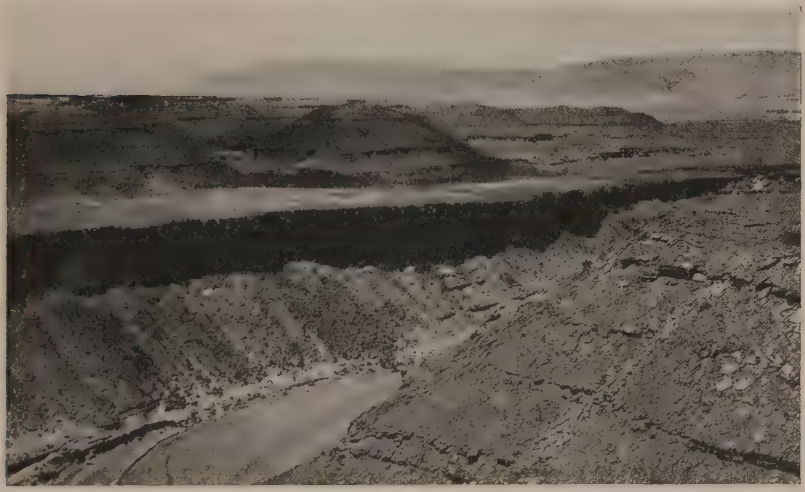


Fig. 429. — Permian shales, sandstones, and lava flow (flat bench in center of picture), Little Colorado Canyon below mouth of Moenkopi Canyon, Arizona. Coconino Point in distance. Photograph from H. E. Gregory.

this time were accumulated the many glacial deposits mentioned elsewhere (page 760).

Deposits in Acadia. — In the Maritime Provinces of eastern Canada the Pennsylvanian is well developed and usually of very great thickness. The celebrated Joggins section of Nova Scotia is 13,000 feet in depth and consists entirely of continental deposits. The Cape Breton series is 10,000 feet thick and the Pictou field has a similar thickness. The Riversdale and Harrington beds (with marine zones) and the plant-bearing strata ("fern ledges" of fresh-water origin) near St. John, New Brunswick, are also of Pennsylvanian age. It is very rare for marine fossils to be reported from this region, and the few that have been found indicate

early Pennsylvanian time. On Prince Edward Island the Permo-Carboniferous has an exposed thickness of over 2000 feet and consists of soft reddish shales and sandstones.

Appalachian Revolution. — Earlier in this chapter it was stated that, with the exception of the Pacific border area, the seas began to vanish toward the close of the Pennsylvanian, and that in early Permian time the continent had again nearly all emerged from the sea. Finally, by middle Permian time probably all of the water

Fig. 430. — Stereographic map of the western hemisphere, after Penfield, showing the position of the Appalachian mountain ranges elevated toward the close of the Paleozoic.

of the Pacific submergence had also been withdrawn, and then for a long time there is no record other than that of continental erosion in both regions.

Previous to this time, the continent, during the Paleozoic era, had been deformed in the east at least four times, although none of these disturbances had the significance of a revolution (see page

579). These were the Green Mountains, Taconic, Shickshockian, and Quachita disturbances. Each one, in turn, folded some area of Appalachia, and since the Taconic Disturbance at the end of the Ordovician there had been laid down in the Appalachian trough of Pennsylvania a maximum of 26,390 feet of strata (6490 Silurian, 13,000 Devonian, 4400 Mississippian, and 2500 Pennsylvanian). It was not alone the loss of balance between the area of loading and sinking (Appalachian trough) and those of erosion and unloading (Acadia and Appalachia) that started the revolution, but it was primarily due to the shrinkage of the earth, possibly as the result of cooling, thus causing the earth's circumference to shorten through folding.

During the Appalachian Revolution much of eastern North America was again thrown into pronounced folds, faulted and widely thrust to the west and northwest (see Fig. 430). This deformation was greater than at any other time before or after, and the area of folding reached from Newfoundland to Alabama, and westward to the Allegheny and Cumberland plateaus. The amount of compression in Oklahoma, Arkansas and the southwest, and along the Pacific is not yet known and may have been slight, but volcanoes were active from California to Alaska. Finally the continent was completely emergent, and it was as extensive then as now or as at any time since the close of the Proterozoic. In other words, the Appalachian Revolution was one of the most critical periods in the history of the earth, and may have been the greatest of them all in its results (see Figs. 427 and 430).

How high the Appalachian Mountains stood in late Permian times cannot be stated. On the basis of the folds that have been measured in Pennsylvania, it has been suggested that they may have been 5 miles high. However, we must not forget that these folds are not altogether due to the Appalachian Revolution, but are the result of this grander movement plus at least four earlier disturbances. These mountain ranges certainly must have had peaks 3 miles high.

Life of the Closing Paleozoic Periods

Cosmopolitan Land Floras. — We have seen in earlier chapters that plant combinations or floras are not known earlier than the Middle Devonian. Although their description is deferred to the following chapter, it may be stated here that with the Pennsylvanian, land plants began to be common in America, that the floras were then large and varied, and also that if we do not restrict ourselves too much to details, these floras, and the land animals as well, were not only very much alike in the different lands of the northern hemisphere, but that there was a marked similarity even

Fig. 431. — Pennsylvanian flora and amphibia, as restored by J. Smit. In the background are *Sigillaria*, with tree ferns and conifers in the middle distance. In the foreground are *Calamites* and Cycadofilicales. Amphibia are represented by a small four-limbed microsaurian (*Keraterpeton*), a large-headed form (*Loxomma*), and a snake-like, gill-bearing stegocephalian (*Dolichosoma*, from Linton, Ohio). From Knipe's *Nebula to Man*.

between the floras of the two hemispheres in the earlier half of Pennsylvanian time (see Fig. 431). In other words, the floras, and to a lesser extent the faunas, were cosmopolitan, and their similarity was undoubtedly due to equable climates and easy migration across the extensive east-west continent Eria. Their distribution was further facilitated by the fact that most of the plants had *spores*, or microscopic reproductive germs, which could be widely blown about by air currents (see Pl. 25, Figs. 4–6).

Toward the close of Pennsylvanian time these floras underwent marked changes. In Europe the older one vanished more rapidly than in America, and its place was taken by forms that became prevalent in Permian times, and some of which later reached America. The latter floras, however, still continued to be cosmopolitan in character.

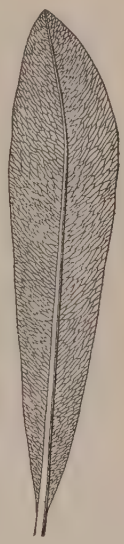


Fig. 432. — Leaf of the Permian net-veined fern *Glossopteris* (*G. indica*). From Credner's *Elemente der Geologie.*

Cool Climate Flora. — In the southern hemisphere, due in all probability to the cool climate brought about by the Permian glacial period, to be described later in this chapter, the older cosmopolitan flora was largely exterminated and a different one evolved, known as the *Glossopteris flora* because of the prominence in it of the fern *Glossopteris* (see Fig. 432). This flora was less striking, both in size and variety, than its predecessor, and less luxuriant, but hardier, and with thicker and less ornate leaves. It appeared at about the same time in Africa, South America, Australia, Tasmania, and southern India; and before middle Permian time some of the forms had attained arctic Russia. Through the commingling of the hold-over Pennsylvanian and Permian floras and their further evolution in a semi-arid climate were brought about the plant assemblages of the succeeding Triassic time. The Glossopteris flora is also known in Antarctica.

Insects. — According to Handlirsch, the Viennese authority on fossil insects, there is no evidence of these animals older than the Lower Pennsylvanian. However, there is good ground for believing that they may have arisen in the Devonian (see Pl. 22).

The size of Paleozoic insects was truly astonishing. Out of four hundred forms known from the Lower and Middle Pennsylvanian,

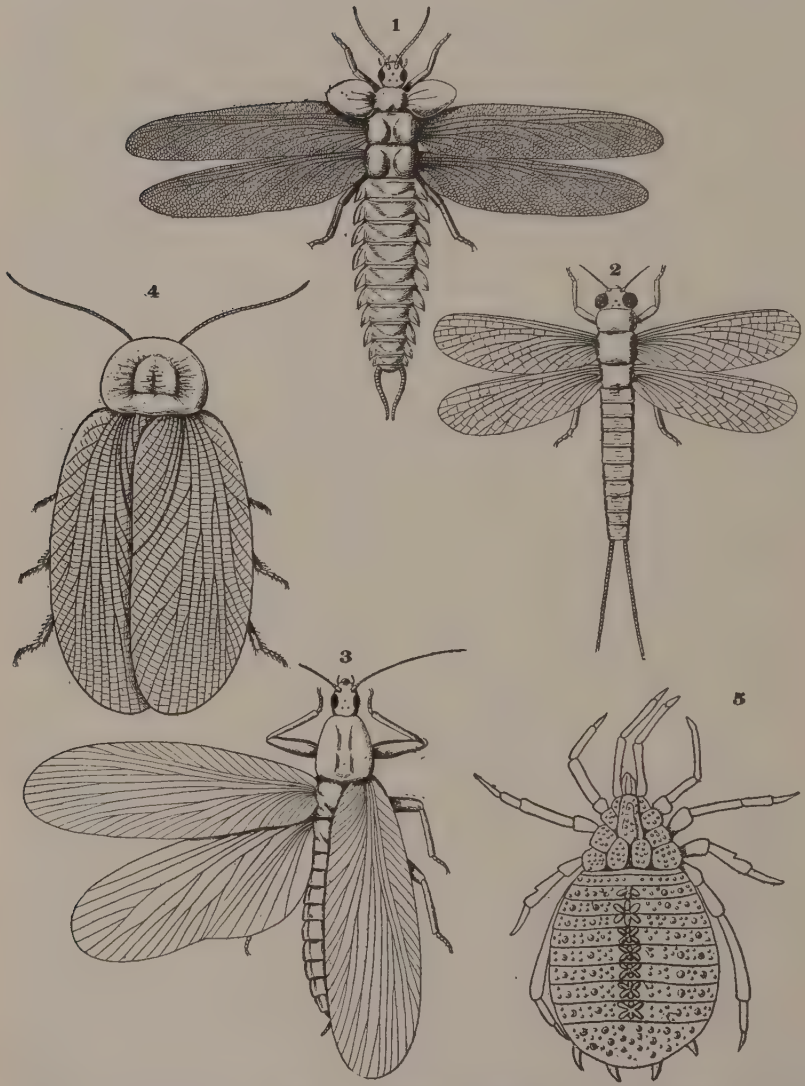


Plate 22. — Pennsylvanian insects and spider. Mainly after Handlirsch. Primal insects or Palæodictyoptera (1, 2), ancestral cockroach (3), true cockroach (4), primitive spider (5). See Appendix B.

only one had a wing length of 0.38 inch, while over twenty had a length of 4 inches, six attained to nearly 8 inches, and three to 12 inches or more, the average being 2 inches. In the Upper Pennsylvanian none exceeded 2.5 inches, and this decline in size continued throughout the Permian and Triassic and culminated in early Jurassic time. At no period since the Paleozoic have insects grown so large, and their rapid decrease in size in the Pennsylvanian, Handlirsch states, can only be connected with the colder climate of early Permian time.

The Pennsylvanian well deserves its title of the *Age of Cockroaches*, since more than five hundred kinds are known from rocks of this period (Pl. 22, Figs. 3, 4). They were mainly carnivorous, and as a rule large, several attaining a length of 3 to 4 inches. While no species were common to America and Europe, their resemblances are marked, indicating an easy land passage from one continent to the other.

There are now known about one thousand species of insects from the Pennsylvanian and Lower Permian strata. They are still scarce in the Lower Pennsylvanian, but in the middle and upper thirds of the system are common. The oldest forms, known as Palæodictyoptera, were especially prevalent in the Pennsylvanian but none lived beyond it (see Pl. 22, Figs. 1, 2). They were, as a rule, large in size and of primitive structure, and led an amphibious life, their youngest or larval stage being spent in the water. In general, they were not carnivorous animals, but as they had powerful chewing mouths it is thought that they fed on plants and on sluggish or dead animal matter. They had four straight wings, all alike, which projected sideways like those of the modern dragon-flies and could not be folded back over the abdomen as in most modern insects. The thorax had three large segments, followed by a long and slender abdomen in which the segments were alike, ending in two long cerci or appendages connected with the breathing organs, as in the living may-flies. Their eyes were compound and their antennæ simple. About 150 species are known.

These primal insects, which are thought to have arisen from the trilobites, gave rise to several transitional stocks, which in turn changed into the modern insects, such as the dragon-flies (Odonata), cockroaches (Blattoidea), and grasshoppers (Orthoptera). In most of the transitional insects the wings were still straight and not capable of being folded. The largest were the carnivorous dragon-flies, one of which, found in the Coal Measures of Belgium, measured 29 inches across the wings.

After Middle Permian time a great change took place among the insects, for the few that are known from this time are not only smaller but are more like modern forms. Judging from the insects of Triassic times, we see that those of the later Permian must have introduced complete " metamorphosis " (a transformation, as maggot to fly or caterpillar to butterfly) in their growth from the egg to the adult, and also resting stages because of winters or seasons of drought and absence of food, as is done by modern forms. This fundamental change is also attributed to the glacial period of Permian time.

Scorpions and Spiders. — In the Pennsylvanian are found scorpions, which, ancient as they are, much resemble those of modern times. Associated with them we see many forms of rather stout spider-like animals, having a distinct cephalothorax (head-trunk), and usually a large abdomen, the latter with four to nine segments; in none of them, however, are known anal spinnerets, or organs for the making of webs (see Pl. 22, Fig. 5). Those with smaller abdomens, and therefore nearer the true spiders, also occur in the Pennsylvanian rocks, but are very rare fossils.

Thousand-legs or Myriapoda appear for the first time in the Lower Old Red of Scotland and are plentiful in association with the Pennsylvanian floras of America. The average species was about 2 inches in length, but at Mazon Creek, Illinois, there lived one that had a length of about 12 inches and was 0.75 inch thick. Like the trilobites, these insects all had double pairs of legs. The head was large, and had great lateral compound eyes, in some of which there were a thousand lenses. In habit some at least were amphibious, and others appear to have been completely adapted to the land.

Land Snails. — There is no evidence of air-breathing or land snails until Middle Pennsylvanian time, when at least six species are known. The greatest number of individuals have been taken by Dawson from the hollows of fossil tree stumps (*Sigillaria*) at South Joggins, Nova Scotia. All of the species are small and are found associated with land plants in coal-swamp deposits.

Land-living Vertebrates. — In the Pennsylvanian and Permian deposits there is much evidence of the presence of many kinds of Amphibia (twenty genera) and Reptilia (forty genera), and their bones become increasingly more abundant in the strata of later times, as described in Chapter XLIV. The Amphibia are most common in the Pennsylvanian, and their origin goes back to at least the Middle Devonian. The Reptilia, on the other hand, which dominated the land of Permian time, appeared first in the Upper Pennsylvanian (see Pls. 27, 28).

The evolution of the air-breathing vertebrate life of the Carboniferous, Williston says, is the most important phase of the whole progress of evolution, for at the close of this period we find forms foreshadowing the chief groups of modern times. The predominant types of the Pennsylvanian were Amphibia, for the most part small creatures related to the living salamanders and known as *branchiosaurs* and *microsaurs*. They were rather sluggish animals living about or in the water, as is indicated by the known larval stages of branchiosaurs. They were more or less protected against their enemies by an external bodily armor, but vanished long before the close of the Paleozoic. It is among the microsaurs, however, that we find a distinct advance toward a higher existence away from

the water, and in the direction of the reptiles. Some lost the dermal armor completely and became fleet of movement, best seen in the structure of the limbs, which mimic so closely in form and structure those of the modern quick-running lizards as to be practically indistinguishable. We may be assured that some of them before the close of the Pennsylvanian were inhabitants of high and dry lands where fleetness of movement, rather than obscurity in coloration and habitat, preserved them from their enemies, and that they were crawling reptiles in everything save in some technically significant details of their palates. Specialization of the microsaurs had reached the extraordinary extent of snake-like, limbless forms.

In addition to these two types of amphibia we have two others: the temnospondylus type, in which the vertebræ are divided into separate elements, and from which the mammals eventually arose; and the stereospondylus type, which terminated in the gigantic labyrinthodonts of the Upper Triassic. (Williston.)

Of *Permian vertebrates*, by far the richest and most varied fauna known is that of America, especially of Texas and Oklahoma. It was an independent and isolated development that had no intercommunication with the reptiles of other continents until well into Triassic time. The faunistic evolution here produced striking results, but does not seem to have been the direct line into the higher and more modern vertebrate stocks.

At least three very distinct phyla of reptiles and as many of amphibia are known. Among the reptiles occur the *pelycosaurs* (*Naosaurus*, *Dimetrodon*), derivatives of a prior type which had branched off before the close of the Pennsylvanian; the true *cotylosaurs* (*Diadectes*), with, in some cases, singular developments of dermal carapace, or armor, strongly suggestive of the turtles and unknown elsewhere; and a third type (*Labidosaurus*, *Pariotichus*) of small crawling reptiles with large head, short tail, and short limbs, whose nearest, but remote, relatives are found among the pareiasaurs of South Africa. (Williston.)

Life of the Seas. — The invertebrate marine life of Pennsylvanian time was not only prolific but also very varied. It was, moreover, a cosmopolitan one, the Coal Measures faunas being everywhere very similar. In Kansas are known nearly 400 kinds of invertebrates; of shelled forms alone there are 234, divided as follows: brachiopods 46, bivalves 111, gastropods 51, and cephalopods 26. The commonest shelled animals were the spiny productids. All of this cosmopolitan life was, however, blotted out before the close of the Paleozoic (see Pl. 23).

Brachiopods are the common fossils of Pennsylvanian time, but toward the end of this period in America they were no longer prom-

Plate 23. — Pennsylvanian Protozoa (1, 2, Fusulinidæ), brachiopods (3–16, 5–11 productids), bivalves (17–21), and gastropods (22–24), and the last trilobite (25).
See Appendix B.

inent, their places being taken by the bivalves. The same faunal change also went on in northern Europe, but in the Mediterranean region (called Tethys) extending from Sicily into India, the waters still swarmed with brachiopods into Permian time. Here the Paleozoic invertebrates made their last stand, but geologic history shows that only a few of them lived on into the Mesozoic seas. A new evolution among the brachiopods then took place, but there never again was such a variety of form as characterized the Paleozoic. While the brachiopods were vanishing, the shelled cephalopods in the goniatid and ammonid stocks were rapidly changing into a

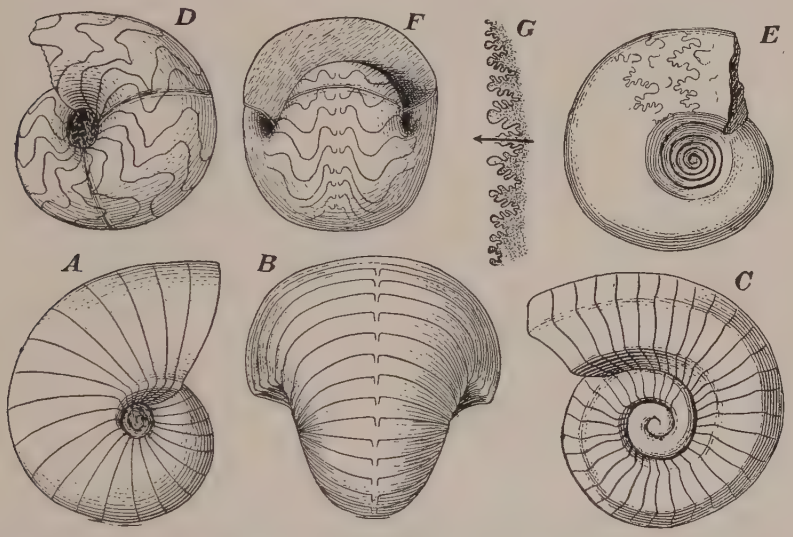


Fig. 433. — Characteristic cephalopods of the Pennsylvanian. *A–C*, nautilids; *D*, *F*, goniatids; *E*, *G*, ammonids. See Appendix B.

variety of forms characteristic of Permian times (see Fig. 433). In later chapters we shall see how these "Ammon's horns" abounded in the Mesozoic seas.

Fusulinids. — Among the minute and lowly organized animals little has as yet been said about the Protozoa, whose individual organization is contained in a single cell, and which represent the first form of animal life. These Protozoa are tiny, naked or shelled globules of streaming protoplasm, with a central, more solid sphere known as the nucleus, which is the actual seat of vital energy or life. They sometimes live singly, but more commonly are combined into colonies. They are known as fossils since the Middle Cambrian, but were not rock makers until later Mississippian time.

The forms with calcareous shells are known as the *Foraminifera*, a name referring to the numerous perforations in the shell. Of these, in the Pennsylvanian and early Permian the forms known as fusulinids (meaning *spindle-form;* the colonies look like grains of wheat) abounded on the bottoms of the seas and were often limestone makers (Pl. 23, Figs. 1, 2). They are known almost everywhere in the northern hemisphere where Pennsylvanian deposits occur. Even in far northern Spitzbergen above 76° north latitude their fossils are still abundant. Similar colonial foraminifers live to-day only on the bottoms of warm-water seas and on coral reefs.

Climate

Warm Climate of the Pennsylvanian. — According to the record of the " life thermometer " it is evident that in early Pennsylvanian time the climate was warm and humid. Great swamps in many lands of the northern hemisphere were storing vast quantities of coal — carbon taken from the atmosphere and water — and even greater amounts of carbon dioxide were being laid away in the limestones of the seas and oceans. Proof of a mild climate is found in the luxuriant coal floras, which are devoid of all evidence of a non-growing season, that is, the logs have no growth or annual rings; in the profusion and great size of the insects; in the wide distribution of the fusulinids; and in the occurrence of coral reefs in Spitzbergen. With the rise of the European Alps the floras underwent changes, and these changes were more marked in that continent than in America, for the floras and insects of earliest Permian time in the United States still indicate a climate devoid of winters, though the air was drier, the red beds and gypsum deposits pointing rather to a semiarid climate. Finally, the seas in all places lost their fusulinids, but the waters were still fairly warm in Tethys (the Mediterranean region), for in Middle Permian time the invertebrate faunas there were profuse and well developed. The cold climate of the early Permian had not yet affected the temperature of the shallower seas of the northern region, but later it is thought that even here the oceans became colder, causing a great dying out of the Paleozoic stocks of animal life. After the Middle Permian the climate of the lands seems everywhere to have been arid and semiarid and this condition lasted into Jurassic time.

Great Glacial Period of Permian Time. — For nearly fifty years geologists have described unmistakable glacial deposits of Permian

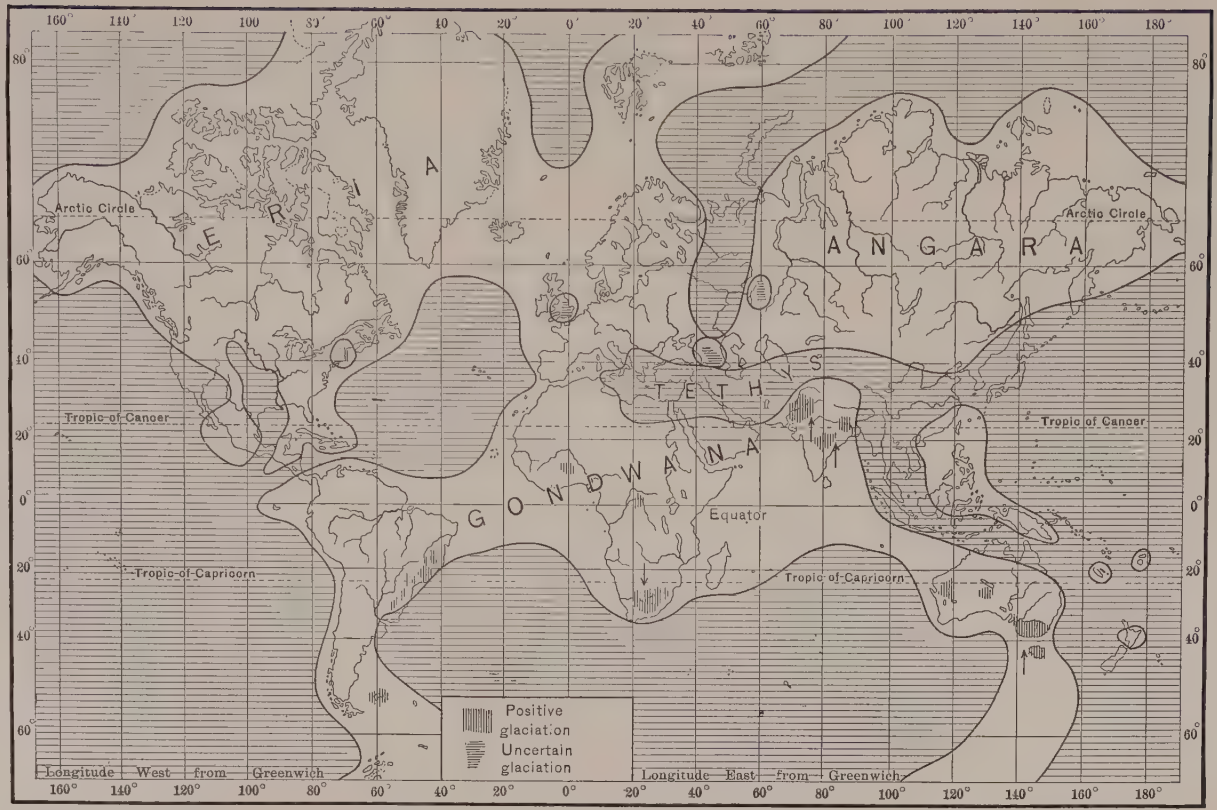


Fig. 434. — Paleogeography and glaciated areas of early Permian time. Note the transverse shape and the connected condition of the continents. Arrows indicate the direction of glacier flow. Carnegie Institution of Washington.

age in the continents of the southern hemisphere, but it is only recently that their results have been widely accepted. It is now known that glacial deposits — bowlder clays called tillites — are of wide distribution, for eight or nine such beds occur in South Australia above the Coal Measures, some of them 200 feet thick, interbedded in 2000 feet of marine strata; in Africa, the thick Dwyka series (1300 feet in Natal) extends from the southern to the central part of the continent; and in India the very thick glacial deposits (Talchir) preceded the Permian submergence. In North America, tillites seemingly of Permian age are known about Boston, Massachusetts, and striated stones have been reported on Prince Edward Island; in England and Germany also they occur at the base of the Permian. For the complete distribution of these glacial deposits, see Fig. 434.

The Permian glacial formations are found on either side of the equator from about 20° to 35° north and south latitudes, but little evidence of this kind is as yet known above 35° in north temperate lands. Further, the climate of that time was arid in the United States and in northern Europe, as is proved not only by the red beds, but even more by the great accumulations of gypsum and salt.

The evidence is now unmistakable that early in Permian times all of the lands of the southern hemisphere were under the influence of a glacial climate as severe as the polar one of recent times, and that, like the latter, the Permian one also had warmer interglacial periods, for coal beds occur associated with the glacial deposits in Australia, South Africa, and Brazil.

Cause of Permian Glaciation. — What brought about this great change in the climate of Permian time, and why it was, apparently, mainly restricted to the southern hemisphere are as yet unsolved problems. Most geologists look for the explanation in the great derangements of the air and oceanic currents brought about by the upheaving of mighty mountain chains, such as the European Alps and the Appalachians (Figs. 427 and 430). Naturally, such upheavals must have altered the outlines of the continents as well, and so brought about alterations of the oceanic currents. Even the carbon dioxide content of the atmosphere (and ocean) may have been lessened, and thus contributed further to the production of the colder climate.

Gondwana and Tethys

Gondwana, the Great Southern Transverse Continent. — Something about this continent has been stated in Chapter XXI, and now further proof of its existence must be given. Such evidence relates mainly to wide-spread deposits of Permian age which have a flora in their lower beds that has been called the *Glossopteris flora* (Fig. 432). This flora occurs throughout the southern hemisphere, and paleobotanists hold that it could only have been so widely distributed across a continuous land (see Fig. 434). Belief in the existence of Gondwana is wide-spread among European geologists, but many American workers do not yet believe in it, mainly because they hold strongly to the theory of the permanence of the oceanic basins and continents. Without this continent, on the other hand, paleontologists cannot explain the known distribution of Permian land life, and, further, its presence is equally necessary for the interpretation of the peculiar distribution of marine faunas beginning certainly with the Devonian and ending in the Cretaceous.

Tethys, the Greater Mediterranean. — To the north of Gondwana lay the great medial ocean which Suess has named *Tethys*, after the consort of Oceanus (see Fig. 434). The present Mediterranean is a remnant of this once grand middle ocean which widely overlapped northern Africa, southern Europe, and Asia, and long extended unbroken from France and Spain into the eastern Indian and Pacific oceans, from time to time connecting with the Arctic Ocean by way of the Ural geosyncline. How often it was in open connection with the Atlantic is not yet clear, but that it had such communication is seen in the similarity of certain southern European and Gulf State faunas (Helderbergian, Kinderhook, and Comanchian).

CHAPTER XLII

RISE OF THE LAND FLORAS

Plants of some kind occur in all lands and under all climates. They are not restricted to the moist soils of the valleys, but live also on the highest mountains and even sparingly in the driest deserts. In the shallow fresh waters are found many kinds of plants, and on the ocean bottoms down to a depth of about 600 feet grow the attached seaweeds. Fastened to rocks, trees, and other objects are the brown and gray lichens, a thin film of spreading plant matter. In the moist forests and on the meadows occur the fungi, including the common toadstools, plants devoid of chlorophyl and feeding on the humic material (vegetable mold) of other dead and dying vegetation. A vast variety of microscopic plants, the bacteria, live everywhere — in the soil, in nearly all waters, in the oceans, on and in other plants and animals. The yeast bacteria convert sugar into alcohol by fermentation, and are used in the making of alcoholic liquors; other bacteria are useful in the making of cheese; still others cause diseases, and are found even in all healthy organisms.

Paleozoic Floras. — From the geologic record we learn that the first known flora came into existence in the latter half of Devonian time, though a few land plants are known from the Silurian. We are probably right, however, in considering that the low-lying lands were clothed with a green verdure from the beginning of Paleozoic time, but that the early plants had not yet acquired sufficient woody tissue in their organization to be preserved in the sediments, and hence have no significance in Historical Geology. Since Middle Devonian time land plants with woody tissue have become more and more prolific and have grown to greater dimensions and higher stature, all of which means that they also have gradually attained a longer individual growth.

Swamp Life of Pennsylvanian Time. — The coal floras of late Paleozoic time are now well known and it is estimated that three thousand species have been described (see Figs. 431 and 435). Probably more than one half of this number were spore-bearing, and we may safely regard the more common plants of the Coal

Fig. 435. — Pennsylvanian swamp flora, as restored by Unger. Note the majestic *Lepidodendron* trees, with tree ferns and Cycadofilicales in the middle distance.

Measures as seedless. Many great trees were present, attaining a height of over 100 feet, with a diameter of 3 feet, and the bulk of the forest must have reared its top higher than 40 feet. It was a forest of rapid growth, of soft and even spongy woods, in which evergreen trees with comparatively small, needle-like leaves were prominent. Associated with these were thickets of rushes, also of very rapid growth, which in habit resembled the living cane brakes and bamboo thickets (Fig. 431). Here and there stood majestic fern-like trees, while many smaller ferns and fern-like plants thrived in the shady places or climbed about the trees (Fig. 435). Shades of green were the dominant color, and the monotone of the verdure was nowhere enlivened by bright flowers. Such, however, were sparingly present, but of a low order, insignificant in size, and unattractive in color. At the time when the trees and ferns were liberating their spores the entire forest was covered with a greenish-yellow or brown dust.

Spores (Pl. 25, Figs. 4–6) differ from seeds in that the latter give rise directly to sexed plants, while the former also develop into sexed ones, but these are short-lived and in turn give rise to the sexless, long-lived plants that bear the spores. In other words, the spore plants have an "alternation of generations," while the seed plants have direct development. This matter will be taken up again later in the chapter.

The air was not scented with sweet odors, for there was no honey, but it is probable that resinous smells such as pervade living conifer forests were present.

In these forests of Pennsylvanian time might have been seen flying about the largest insects that have ever lived, great dragon-flies reaching a wing spread of over 2 feet. Huge cockroaches abounded everywhere in great variety, giants of 4 inches in length not being rare (see Pl. 22). As a rule, these insects were carnivorous, and did not transfer the pollen from one flower to another as is so commonly done by living insects among present-day plants. The smaller forms were preyed upon by scorpions and spiders, the latter not making webs but living on the ground or in rotten logs, along with many myriapods, or thousand-legs. No insects of this time, so far as known, produced chirping or other sounds, and the soughing of the wind among the trees was possibly rarely interrupted save by the croak of an amphibian in the marsh. Reptiles and amphibians were common in the swamps, and it is probable that many small reptiles were running over the ground and about the trees. No larger land animals, such as we know, and no birds were to be seen.

Vascular Plants. — In this chapter we are to study only the earliest land plants, and as these can be preserved as fossils only if they have fibrous or woody material, the paleontologist is not directly concerned with the lower Cryptogams, such as the microscopic bacteria, the lichens, fungi, or even the mosses.

Plate 24. — Filicales (1, tree fern; 2–5, doubtful ferns) and Cycadofilicales (6–10). See Appendix B.

All of the higher plants above the mosses in organization are characterized by having roots, and by the occurrence in their soft tissues of what are known as *vascular bundles*. These bundles are composed of tough, hollow, interlacing fibers, whose primary function is to serve as conducting channels (hence vascular, from *vasculum*, a small vessel) through which the various food materials pass; secondarily, they are of importance as forming supporting skeletons of the plants. All of the woody material is composed of these strands, and it is this tough substance which makes it possible for leaves and other parts of plants to impress upon the sediments the traces of their former existence.

Classification. — For our purposes, Paleozoic land plants are most conveniently divided into (1) those which have no flowers but reproduce by spores and go through an alternation of generations, as explained beyond; and (2) those which have flowers and reproduce directly from seeds. Of the first subkingdom, the Cryptogams, only the phylum *Pteridophyta* will be considered; this group includes the ferns and also plants that resemble the ferns only in their method of reproduction, such as the rushes and lycopods (see Pls. 24–26). The second division, known as *Phanerogams*, embraces the seed-bearing fern-like plants (Pl. 24, Figs. 6–10), the evergreen trees or conifers, in which the flowers are small and inconspicuous (Pl. 26, Figs. 3–6), and the true flowering plants or Angiosperms.

Spore–bearing Plants or Pteridophyta

Equisetales or Rushes

Among living plants there is a small group of forms having a very wide distribution and known as Equisetales, or rushes (similar to Pl. 26, Figs. 1, 2). As a rule, they are small, less than 18 inches tall, appearing in wet places early in the year; in Central and South America and Cuba, however, a giant form occurs in groves, attaining a height of 40 feet, but with a stem that does not exceed an inch in diameter. This and all other living forms, twenty-five in number, belong to the genus *Equisetum* (see also Fig. 435).

This living genus of rushes has in the ground a non-sexed, perennial, creeping and branching, horizontal root-stalk, that at intervals gives rise to upright aërial stems and descending roots. The stems consist of a thin, externally striated, woody zone, with a large pith center. At regular intervals the stem is divided into *internodia* by transverse partitions called *nodes*, and from these arise

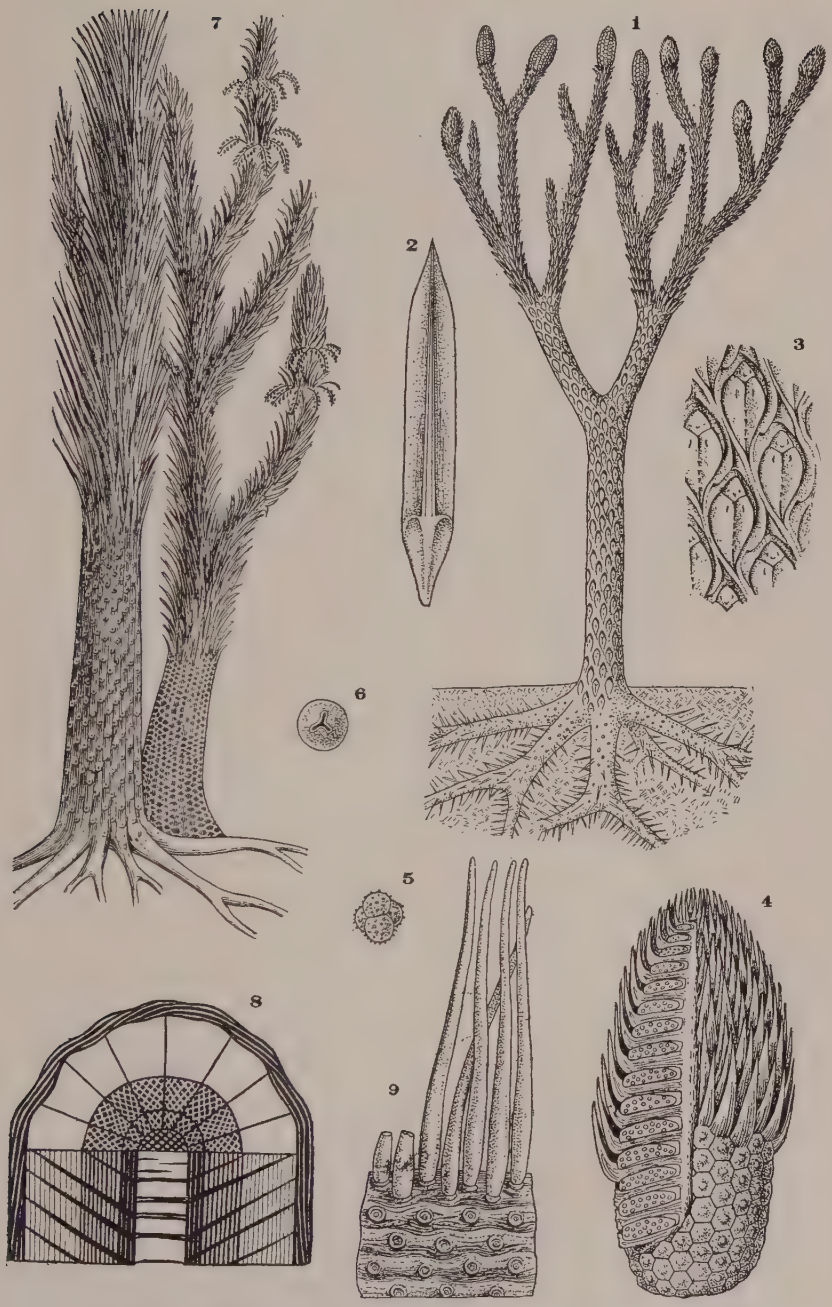


Plate 25. — Lycopods of the Pennsylvanian. 1–3, *Lepidodendron;* 4, cone with spore cases; 5, four microspores; 6, a macrospore; 7, *Sigillaria;* 8, trunk in section; 9, root or *Stigmaria*. See Appendix B.

the circles of small or reduced leaves, with one or more longitudinal veins, and also the branches when such are present. The branches repeat on a smaller scale the general features of the stems. At the top of the stem or on the branches occur the spore-bearing cones. The sexless spores, which are all alike (*homospores*), are short-lived, and give rise to small, lobate plants known as *prothallia*, or first growth, which develop both male and female organs. The prothallia give rise in turn to the fertilized egg-cell out of which grows the *Equisetum*, completing the developmental cycle from the persistent sexless generation to the sexed plant of short duration.

Fossil Calamites. — In Paleozoic time, from the Devonian to the Permian, but more especially in the Pennsylvanian, lived a great variety of other Equisetales known as the Calamites (Pl. 26, Figs. 1, 2). They were prolific plants which attained to a height of 60 and even 90 feet and a diameter of 15 inches. In them the wood cylinder was far thicker than in *Equisetum* and specimens are known having 2 inches of bark outside of the same thickness of wood. The layers of secondary wood were added externally beneath the bark, a type of growth found in modern trees. The nodes were not equidistant throughout as in the living forms, but in the earliest growth were progressively farther apart, and the stems thickened rapidly. Calamites were also far more abundantly branched than is the case in *Equisetum*, and their leaves were proportionately larger. The top of the trunk consisted of a crowded tuft of closely set circles of leaves. The cones with reproductive spores occurred more or less abundantly on the smaller leafy twigs or at the top of the main stem. As a rule, the spores were all alike, but in some cases they were differentiated into small and large types (*heterospores*, see Pl. 25, Figs. 5, 6).

Calamites occur commonly as casts of the pith cavity into which the sand of the deposits penetrated as the pith and the nodal partitions decomposed. The linear furrows seen on these casts are therefore the characteristics of the inner pith cavity of the trunk, and it is rare to find impressions of the outer side. The circles of leaves are also common fossils, and are known as *Annularia*.

Lycopodiales

Living Lycopodiales. — Lycopods is a group name for the very widely distributed, primitive, herb-like plants known as ground pines, club mosses, and running pines, the latter being extensively used in floral decorations. There are about one hundred living species of the genus *Lycopodium*, the name, from the Greek for *wolf's foot*, being given because of the appearance of the roots. In

the existing floras the lycopods never grow in dense masses to the exclusion of other plants, and therefore are not conspicuous. Their general appearance suggests the larger mosses or smallest branches of pines, since the leaves are always remarkably small.

In the Paleozoic, however, from Devonian to Middle Permian time, but more especially during the Pennsylvanian, the lycopods were the dominant plants, and attained to gigantic proportions when compared with the living representatives, for they were then at the climax of their evolution (Figs. 431 and 435). These trees in Pennsylvanian times liberated their heterosporous reproductive germs in such tremendous amounts as to be a factor in coal making (see Pl. 25, Figs. 4, 5).

Lepidodendron or Scale Tree. — Among the Paleozoic lycopods, the evergreen *Lepidodendron*, which receives its name from the scale-like appearance of the leaf-bases, was the most prominent in abundance and variety of form; upward of one hundred species have been described, ranging from the Devonian to the Permian (Pl. 25, Figs. 1–6). The trunk tapered slowly and in some forms grew to a height of over 100 feet and a diameter of 3 feet. These trees in their general appearance differed from all modern ones in that the trunk and many of the branches divided into two forks rather regularly. The more slender branches were terminated, as a rule, by linear or oval spore-bearing cones 1 to 12 inches long (Pl. 25, Fig. 4), agreeing in size and form, but not in internal structure, with the seed-bearing cones of the spruce, fir, and other conifers.

Basally, both *Lepidodendron* and *Sigillaria* (to be described later) terminated in from four to seven trunk roots that are thought to have spread almost horizontally in the ground, and there was no vertical, or tap root, continuing the trunk as in modern trees. These trunk roots each divided once or twice and tapered to a point, burrowing in every direction through the mass of decaying vegetation in the swamp. Their surface was marked by circular scars arranged in sets of five, and to these were attached round tapering appendages radiating in all directions; these latter attained a length of 15 inches and served for the extraction of food and water from the ground (Pl. 25, Fig. 9). Such roots are known as *Stigmaria* (from the Latin *stigma*, a mark), and are very frequently seen in the underclays beneath coal beds.

The leaves of *Lepidodendron* were needle-like, always comparatively small, but having a width at the bottom of 0.5 inch and a length of 6 to 7 inches (Pl. 25, Figs. 1, 2). On their under sides

there were two lateral grooves, and in these hollows were situated the minute but numerous breathing organs for the extraction of the carbon dioxide from the atmosphere. The leaves soon dropped off, and are usually found attached only to branches of small size, that is, the young growing twigs. The leaf-bases were more or less diamond-shaped, vertically elongated, and arranged on the branches and trunks in spirals, thus forming the characteristic markings of the trees. The leaf was attached in the upper part of the rhomb, and when well preserved bears three scars or pits, one of which is a vascular canal through which the plant fluids or food passed from the inner wood cylinder to the leaf, or in the reverse direction (Pl. 25, Fig. 3).

Trunk of Lepidodendron. — The structure of the trunk and branches was peculiar in that the greater thickness beneath the outer layer with the leaf scars was composed of two kinds of cork-like bark surrounding a comparatively thin internal woody cylinder that may have been entirely filled with inward growing wood or with more or less of pith (Pl. 25, Fig. 8). Secondary wood up to 2 inches thick was added to the outer cork beneath the leaf layer, and as this cork was also tough, the trees, even though tall, had considerable resisting power against the winds and storms of that time but were less stiff than the modern forest trees.

Spores of Lycopods. — The cones of fossil lycopods, while they looked much like those of modern evergreens or conifers, did not have seeds but were filled with spores (Pl. 25, Figs. 1, 4–6). The latter grew in large cases (*sporangia*) and contained either minute spores, the *microspores* or fertilizing male parts (Pl. 25, Fig. 5), or large ones, the female *macrospores* (Pl. 25, Fig. 6), often forty times larger than the microspores. These two kinds of spores were developed either in different cones or in different parts of the same cone, and there were many more of the minute spores than of the larger ones. The larger spores would not germinate in the ground until fructified by the microspores, which were washed upon them by the rain water.

Sigillaria. — Associated with *Lepidodendron* throughout the Carboniferous were other evergreen trees known as *Sigillaria*, or seal trees, so called from the shape of the leaf scars (Pl. 25, Fig. 7). Of these one hundred species have been described. They were in general appearance very much like *Lepidodendron*, but the *Sigillaria* stems were rarely branched. Trunks have been found with a diameter, just above the roots, of 6 feet, and other stems are known with a length of 70 feet and a diameter of about 2 feet at one end

and 20 inches at the other. Another specimen attained a height of nearly 100 feet and was unbranched. At the tip, for about 10 feet, these trees were clothed with erect, rigid, grass-like leaves, which in most cases were like those of *Lepidodendron*, but sometimes were far larger and wider.

The leaf scars in *Sigillaria* were arranged very differently from those of *Lepidodendron*, occurring in vertical rows with the scars of adjacent series alternating with one another. When in close juxtaposition they were more or less hexagonal in outline, but when more or less separated they appear rounded in form. In many forms the surface of the trunks was longitudinally ribbed, each of the ribs bearing a single row of leaf scars on its rounded surface (see Pl. 25, Fig. 7).

Trunk of Sigillaria. — The internal structure of the trees was very much alike in both types, but in *Sigillaria* the inner wood cylinder appears to have been thinner and the pith was of larger size. The reproductive cones reached a length of 9 inches and differed from those of *Lepidodendron* only in having a long stem for attachment. *Sigillaria* are unknown in the Devonian and died out before the close of Pennsylvanian time.

Ferns or Filicales

Nearly everyone knows what a living fern looks like, but when this knowledge is applied to the Paleozoic plants of similar appearance, even the best of botanists cannot at present be certain in many cases that the form studied is a true fern. Ten years ago it was believed that fully one half of the Carboniferous plants were true ferns and that these beautiful forms dominated the floras of that time. Due, however, to the accumulation of botanical knowledge, and more particularly to the discovery of specimens bearing the reproductive organs, it is now known that many of the so-called Paleozoic ferns bore seeds and therefore were of a higher organization and must be classified wholly apart from the true ferns or Filicales. These were the *Cycadofilicales*, plants combining the characters of ferns and cycads (plants resembling palms); they were in many ways transitional between the spore-bearing ferns and the seed-bearing plants (see Pl. 24, Figs. 6–10). Probably fully one half of the Paleozoic plants formerly regarded as ferns (about one thousand species) will eventually be shown to be seed-bearing and therefore Cycadofilicales. These are described on page 774, but to understand them it will first be necessary to study the modern ferns.

Living Ferns. — There are living to-day nearly six thousand different kinds of ferns, ranging from tiny, delicate forms to the beautiful

tree ferns of tropical lands, which grow to a height of 50 feet. The greatest variety occurs in the tropics, but they are found under all climates, even in icy Greenland. As a rule, however, ferns prefer wooded humid regions. The fern plant is the sexless generation. Its spores are usually developed on the under side of the leaves in many sori or spore-cases, a number of which are always clustered together. In each sorus there are many microscopic spores which are all alike, and these are often developed in countless numbers (see Pl. 24, Fig. 4).

A few of these spores may germinate in the ground, giving rise to a sexed plant, the *prothallium*, which is usually a primitive, heart-shaped, green shoot lying prostrate on the ground and often less than 0.5 inch in length. On its under side are developed male organs (*antheridia*) that give rise to male cells or pollen, and female organs (*archegonia*) that when fertilized by a male cell develop certain cells into sexless plants. We have here, therefore, an *alternation of generations*, that is, non-sexed plants giving rise to sexed plants, and these in turn producing the non-sexed ferns.

In the smaller herbaceous ferns there is a short, stout, underground stem that gives rise to many leaf stems, each of which develops curled up in a spiral, remaining so for a year or more. Subsequently the stems uncurl and grow rapidly into the fully developed leaves, generally called *fronds*. These may attain a great length, as in the tree ferns, and are called fronds because the leaves are compounded of many leaflets.

In the tree ferns there is but a single unbranched stem resembling a palm trunk, and the fronds, consisting of one or more leaves with their many leaflets, are developed at the top as a crown, each frond uncurling as it attains full growth. The trunk bears the scars of the fronds that have dropped off and beneath this outermost layer there is often a thick zone, the bark, which surrounds the more or less large, central, woody cylinder (Pl. 24, Fig. 5).

Fossil Ferns. — Ferns were very rare in the Devonian and are not common as fossils until the Pennsylvanian, where many species of the smaller herbaceous kinds occur associated with the tree ferns (see Pl. 24, Figs. 1–5). From the structural stand-point the Paleozoic ferns were primitive and it was in the Mesozoic that nearly all the modern forms arose.

Tree ferns became conspicuous for the first time in the Pennsylvanian and were plentiful in the later half of this period and in the early Permian. The stem in some instances attained a height of 50 feet or more, and in certain forms the fronds developed in two or four

Plate 26. — *Calamites* (1, 2) and *Cordaites* (3–6) of the Pennsylvanian. Living maidenhair tree or gingko (7). See Appendix B.

parallel columns, but in most cases they were placed spirally around the trunk. The fronds grew in crowded spirals at the top of the stem (see Figs. 431 and 435).

Seed-bearing Flowering Plants or Phanerogams

The seed-bearing plants are exceedingly varied and numerous, and are divided into two phyla. The geologically older and more primitive division is known as *Gymnospermæ* (naked seed), in which the male and female parts may be in separate flowers or combined into one, but are always inconspicuous and often without bright colors. The seeds develop in the open ovaries, which are said to be naked because the pollen falls directly upon the ovules (eggs), while in the higher plants the ovary is covered by a stigma which receives the pollen. The Gymnosperms include the Cycadofilicales, Cordaitales, Cycadales, Coniferales, and Ginkgoales.

Angiosperms. — The other phylum, which is called *Angiospermæ* (covered seed), embraces the true flowering plants. In these plants the male (anther) and female (pistil) parts are combined in the same flower, which is usually conspicuously colored. The pistil is in the center of the flower, and at the top of it is the stigma covering the ovary sac below. The pollen of the anthers falls upon the stigma and is said to pollinate it, the pollen grains then growing down through the stigma and eventually passing into the ovules and fertilizing them. Hence the seeds are said to be covered. The Angiosperms include the grasses, cereals, bamboo, palms, orchids, the forest trees and the flowering plants generally — forms unknown, however, before the Comanchian.

Cycadofilicales or Seed-bearing Ferns

In discussing the ferns on a previous page, it was stated that there were in the Paleozoic many plants having all the appearance of being true ferns but known to have borne seeds instead of spores. In other words, these plants had no alternation of generations to complete the developmental cycle but were sexed plants, either males developing pollen or females developing seeds which were fructified and developed into an embryo while attached to the plant. As the plants had the general appearance of ferns (technically Filicales) and had seeds very much like cycads, they are called Cycadofilicales (see Pl. 24, Figs. 6–10).

The seeds and pollen were borne on independent sexed plants, the fertile fronds of which were only slightly modified from the non-fertile leaves. The seeds may have been small and occurred at the tips of the leaves or hung down on the under side at the outer ends of the lobate leaves, or, if large, were attached to the thick midrib of the frond; *they never occurred in cones.* The seeds varied

in size from 0.25 inch up to at least 2 inches in length, often being long drawn out at the free end, where the entrance to the pollen chamber was located. The embryo or nut was surrounded by a husk that in some forms had a thick, fleshy exterior and a hard, stony, inner layer. Similar seeds also occurred in the Paleozoic conifers, in the ginkgos (Pl. 26, Fig. 7), and in the cycads.

Some of the Cycadofilicales had long and slender stems, and climbed about other plants; many were herbaceous, and others were as tall and stout as the tree ferns. They had their origin in primitive ferns earlier than the Upper Devonian, and their climax of development was in the Pennsylvanian and early Permian, but none are as yet known beyond the Paleozoic. The Cycadofilicales gave rise to the Cycadales so characteristic of the first half of Mesozoic time.

Genera of Cycadofilicales. — The fern-like plants now referred to the Cycadofilicales include *Lyginodendron*, *Heterangium*, most of the species of *Sphenopteris* and *Pecopteris*, and probably *Neuropteris*, *Alethopteris*, *Odontopteris* and *Dictyopteris;* also *Aneimites* with fronds as in the maidenhair fern of to-day, and *Eremopteris*. Besides these well known groups of plants there are many others that will in all probability be definitely placed among the Cycadofilicales.

Cordaitales or Large-leaved Evergreen Trees

In the Paleozoic, beginning at least with the Upper Devonian, occur logs whose structure is not very unlike that of modern pines or conifers. In the Pennsylvanian, casts of such logs are often seen in the sandstones, and in the roof shales of the coals the long strap-like leaves of these trees abound; in fact, they often form a good part of the coal. These plants, which are known as *Cordaites* (after the paleobotanist Corda), included a variety of forms, and were the dominant Gymnosperms of Paleozoic time. They were softwood evergreen trees, tall and slender, sometimes 120 feet tall and 3 feet thick. In such tall trees fully two thirds of the trunk was without branches, the upper third or fourth of the stem having a dense crown of them and abounding in simple leaves of large size (see Pl. 26, Figs. 3–6).

The leaves in *Cordaites* were always large, and some are known with a length of 6 feet and a width of 6 inches. Some were strap-shaped, with the free ends either pointed or blunt; others were grass-like, with a length of 20 inches and a width of 0.5 inch. The leaf substance was thick and had parallel veins as in the living yucca (see Pl. 26, Figs. 3, 4).

The male and female flowers of *Cordaites* were small, not over 0.5 inch in height, and the catkin-like blooms were arranged on special shoots and often

interspersed between the leaves. The male flowers developed many pollen sacs filled with pollen, while the female ones, though having many ovules, usually developed but a single one into a large seed (0.25 to 0.5 inch). The seed was enveloped in a double coat or husk, the outer layer being fleshy and the inside thinner one dense and hard.

The Cordaitales may have had their origin in the Cycadofilicales, but it is thought more probable that they developed independently out of the most ancient ferns, as did the Cycadofilicales.

While the woody trunk of *Cordaites* was very much like that of modern pines, it is distinguished from the latter by always having a central pith which may be of any diameter up to 5 inches. The new wood was formed beneath the thick bark, in other words, was added externally to the previous layers.

Cordaites was related to the conifers, but, as is seen from the above description, the two groups were very different in their composition. The former were much branched only at the top, did not have cones with seeds but developed them in catkins, the leaves were not needle-like but strap-like, and finally the trunks had a pith center. The *Cordaites* were most closely related to the ginkgos.

Ginkgoales or Maidenhair Trees

Early in Pennsylvanian time there appeared shrubs with short but broadly lobate leaves having parallel veins reminding one of the leaves of the maidenhair ferns. They also suggest greatly reduced leaves of *Cordaites*, and some of the Paleozoic forms may be shown to belong to the latter group. These plants, always rare, are not met with until the Permian, and while they never appear to have dominated any flora, their remains are found throughout the Mesozoic, and at present there is a single cultivated species living in China and Japan, known as *Ginkgo* or the maidenhair tree (Pl. 26, Fig. 7). They appear to have been most common in the Jurassic, and the living genus had its origin as early as Triassic time.

The ginkgos differ from the Cordaites at once in the much smaller and lobate leaves, while the trunks are branched throughout nearly their whole length.

Coniferales or Needle-leaved Evergreen Trees

The evergreen trees whose seeds are developed in prominent female cones and the pollen in male cones are not known to be older in origin than the Permian, but are now the commonest of Gymnosperms. The order embraces the Araucarias, the Sequoias or California "big trees" (closely related but smaller trees can be traced back to the Permian), the pine, spruce, fir, juniper, larch, cypress, and yew.

CHAPTER XLIII

COAL AND ITS OCCURRENCE IN NATURE

Carboniferous Time. — The most conspicuous feature of the rocks of Carboniferous time is the many beds of valuable coal which they contain. In North America nearly all the coal of this time was laid down during the Pennsylvanian period in the eastern United States and the Acadian provinces. In other words, the Pennsylvanian coals of North America occur east of the 100th meridian, while most of the younger coals of Cretaceous time lie in the Rocky Mountains region between this and the 115th meridian. The least valuable coals, of Tertiary time, occur west of the 120th meridian (see Fig. 438).

The more valuable coals of Europe and China were also deposited during the Carboniferous, though in Europe the accumulating began earlier and lasted longer. *By far the greatest amount of the coal in the world was laid down during the time of the Coal Measures;* it has been estimated that seven tenths of it was formed in these, the closing periods of the Paleozoic era. The names *Carboniferous* and *Coal Measures* are therefore seen to be well chosen, since this time was so essentially one of coal making. However, we should use these names only in a general way, as we have seen that this vast lapse of time is clearly divisible into at least three if not four periods.

Oscillatory Nature of the Sea. — The most striking peculiarity of the life of Pennsylvanian time was the wonderful array of plants which, as has been shown in the preceding chapter, constituted the greatest land flora of Paleozoic time, and which furnished the organic material from which the coals in the main have been made (see Pls. 24–26, also Figs. 431 and 435). The most notable physical features were the many and vast swamps, the great majority of which lay near sea-level. This sea-level was inconstant, and although its fluctuations may not have been greater than 50 feet, yet because of the vast extent of the tidal flats, the latter were widely flooded by the risings of the sea. This oscillation of the sea-level was due to the periodic subsidence of the sea floor (as explained in Chapters XX and XXI) preceding the Appalachian

Revolution, and, with every rising, the rivers were dammed back, and the waters over the flats became more or less marine, depositing muds and muddy limestones that often abound in remains of sea life (see Pl. 23). During the upwarps of the land, causing the intervals of ebb, the streams were rejuvenated, scouring away some of the deposits on the previous sea floor and spreading over the low lands the thick sandstones and sandy shales, which very rarely have marine organisms (see Fig. 437, and Fig. 42 on page 56).

Fig. 436. — Map of Cape May Peninsula, New Jersey. Dotted areas show coastal marshes, to illustrate recurrence of coal marshes in Pennsylvanian time. U. S. Geol. Surv.

At these times, and also when the sea basins had been filled with sediment, large salt- and fresh-water marshes and shallow lakes formed, around whose borders became established the marsh floras (see Fig. 436), which in time possessed the entire flats and lake areas and filled the basins with peat or jelly-like masses of carbonaceous material. These alternations between the land and the sea were repeated many times.

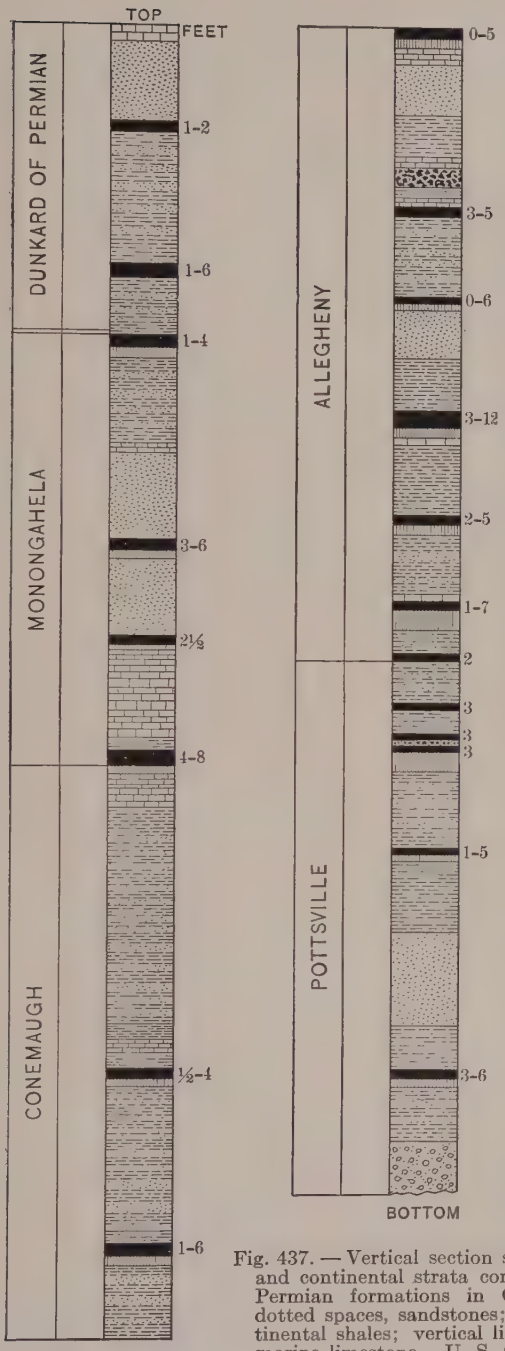


Fig. 437. — Vertical section showing character of the marine and continental strata composing the Pennsylvanian and Permian formations in Ohio. Solid black, coal beds; dotted spaces, sandstones; broken lines, marine and continental shales; vertical lines, fire-clays; block structure, marine limestone. U. S. Geol. Surv.

Pittsburgh Coal Bed. — The greatest coal swamp of Pennsylvanian time was that which made the Pittsburgh coal bed, extending interruptedly for 225 miles in a northeast-southwest direction and 100 miles from east to west. This swamp was twenty-two times greater than the present Dismal Swamp of Virginia-North Carolina; it must not be assumed, however, that all parts of the area were a continuous coal swamp, as there were undoubtedly many intermediate dry places. I. C. White states that the Pittsburgh coal is known to be workable over 6000 square miles of western Pennsylvania, eastern Ohio, and West Virginia, an area six times larger than the Dismal Swamp. The latter, before it began to be drained, covered an area 40 by 25 miles, and is now a great coal field in the making, covered with a layer of peat as much as 15 feet thick in places (see page 166, and Figs. 142 and 144). The Pittsburgh bed at Pittsburgh, Pennsylvania, has a thickness of 10 feet; in the Cumberland, Maryland, region it is 12 to 16 feet, thinning to about 6 feet at Wheeling, West Virginia, and Pomeroy, Ohio.

Variable Nature of the Strata in Coal Fields

Comparison of Different Fields. — The statements given below show very similar sedimenta-

tion in the various states, except that in Indiana the amount of material is less and there is more of mud and less of sand. The small amount of calcareous sediment in Indiana is surprising, but there is more in the Illinois area and it becomes dominant in Kansas. The twenty-five commercially valuable coal beds of Indiana have a fairly wide distribution and at least one occurs throughout the coal field of the state, but the average thickness of the coal beds is probably less than 2 feet. Some of the thicker coals average 6 to 8 feet over several hundred square miles, and one attains a local thickness of more than 10 feet. The valuable coal beds are concentrated within a thickness of 500 feet of sedimentation, with their thickest part in the centers of the various basins of accumulation.

Pennsylvania. — Broadly stated, the Coal Measures of central and western Pennsylvania, including the Dunkard of Permian age, will average about 2600 feet in thickness. To give some idea of the alternation of the strata and the amount of each kind of sediment, the following generalized statement is compiled from several sources (compare with Fig. 437):

27 zones of sandstone or sandstone and sandy shale =	1350 ft., aver. 50	ft.
20 zones of shale (rather sandy) =	748 ft., aver. 37	ft.
28 zones of impure limestone =	340 ft., aver. 12	ft.
29 zones of coal (humic) at their maximum thickness =	106 ft., aver. 3.6	ft.
11 zones of fire-clay at their maximum thickness =	56 ft., aver. 5	ft.
115 zones in	2600 ft., aver. 22.6	ft.

Indiana. — The coal field of western Indiana is the eastern part of the Illinois-Indiana basin, and while the total thickness in the western state is approximately 2000 feet, only about 1300 feet occur in Indiana. According to Ashley, the character of the sediments is as follows:

25 zones of sandstone and shaly sandstones =	708 ft., aver. 28	ft.
39 zones of shale =	408 ft., aver. 10	ft.
13 zones of limestone =	45 ft., aver. 3.5	ft.
25 zones of coal (humic) at their maximum thickness =	90 ft., aver. 3.6	ft.
19 zones of fire-clay at their maximum thickness =	53 ft., aver. 3	ft.
121 zones in	1304 ft., aver. 10.8	ft.

Illinois. — A generalized section by Worthen for northern Illinois gives ninety-five sedimentary zones having a united thickness varying between 1072 and 1722 feet. Of these nineteen are fossiliferous marine horizons, alternating with seventeen coal beds. The latter vary in depth from 6 inches to 9 feet, averaging 2 feet 6 inches, while the marine zones of shale or limestone vary from 1 to 25 feet, averaging 6 feet in thickness.

Kansas. — In eastern Kansas the thickness of the Pennsylvanian-Permian strata beneath the red beds is from 2700 to 3200 feet. The series begins with the Cherokee shales (400 to 500 feet thick) to which are restricted the workable coal beds. Then followed a long period of normal marine deposition. Occasion-

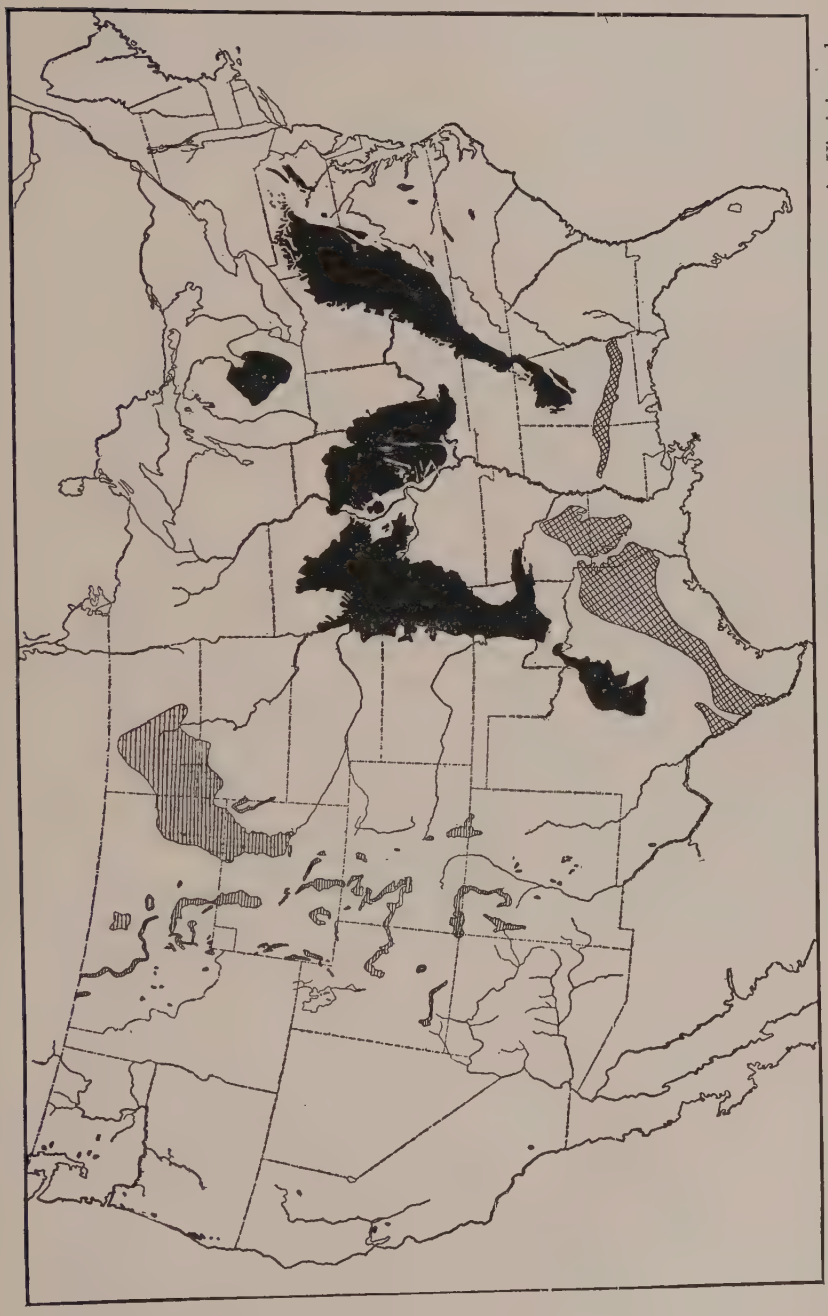


Fig. 438. — Known distribution of coal in the United States. Black areas, coals of Pennsylvanian age, except in Virginia and North Carolina, where they are of Triassic time. Areas with horizontal lines, in the Rocky Mountains country, coals of Cretaceous and Eocene age. Areas with diagonal lines, coals of Tertiary time. U. S. Geol. Surv.

ally, however, local thin sandstones with mica occur, indicating low islands, for in them are preserved land plants. In most of the shale zones are seen very thin local coal streaks of less than 1 inch thickness, which probably represent rafts or drifts of plants floated from the land.

Variability in Sedimentation. — From the above presentation it is seen that sedimentation changed often from sandstone to shale, and it is known, further, that the character of the strata also changes rapidly in its areal extent, that is, geographically. The only fairly persistent horizons are the thicker coal beds and the calcareous zones. In the Mississippi valley marine fossils occur in

Fig. 439. — A vertical *Sigillaria*, 8 feet long and 18 inches wide, rooted in an old soil, Joggins, Nova Scotia.

nearly all the shales and limestones, and as the sandstones and shales are constantly replacing one another, the phenomena presented are those of a very shallow sea, in which were developed from time to time more or less widely distributed and long-enduring salt-water marshes. It was in these marshes that the coal flora grew, as is shown by the fact that the coals of the Mississippi valley have a persistently high percentage of sulphur, a mineral substance always present in marine marshes and almost entirely absent in fresh-water ones. In the Appalachian area the

marine sediments are far less prevalent and the marshes were therefore of greater area and of longer duration.

The Joggins Section. — The Coal Measures previously described were deposits more or less under the influence of the sea. We will now turn to the celebrated Joggins section in Nova Scotia, which is of a different origin, and nearly every foot of which can be studied at the head of the Bay of Fundy.

The name Joggins seems to have had its origin in the "jog-in and jog-out" of the shore. The total thickness of the section here is nearly 13,000 feet, and it appears to be all of Pennsylva-

Fig. 440. — Another *Sigillaria* standing erect in the position of growth, Joggins, Nova Scotia. Geol. Surv. of Canada.

nian age. Throughout this mass of coarse material, very largely tinged with red, no one has yet found an assemblage of genuine marine fossils, or even a single brachiopod or other undoubted sea animal. The fossils are in the main land plants, but these are abundant only in the roofs of the coals, while the drifted and prostrate logs are nearly all restricted to the gray and green sandstones, where they occur as casts. Logan's "Division 4," with a thickness of 2539 feet, is the main fossiliferous horizon with coal formation, and often abounds in fresh-water bivalves, air-breathing

snails, bivalve crustaceans, tiny worm tubes, and bones and tracks of Amphibia; even rain-drop impressions are preserved. It is probable that the invertebrate animals seen in profusion were of brackish-water origin, but had gone farther inland over the river delta and become wholly adapted to the fresh waters. Even the swamps were, as a rule, of short duration and the more persistent ones were often invaded by muddy water which deposited above the underlying pure coals the many black shaly zones.

Fig. 441. — A vertical *Calamites* in sandstone, about 6 feet long and 3 inches wide, Joggins, Nova Scotia.

A further study of the detail of this section shows clearly that it was only the prostrate logs that were rafted away from their place of growth and whose remains are now seen as casts in the sandstones. The coals themselves, of whatever thickness, were made in fresh or brackish water marshes in the places where they now occur, since most of them are underlain by the swamp soils still filled with fossilized roots. Not only this, but there are preserved many additional soils whose exposed vegetation was swept away by the waters that brought the invading and covering muds and sands. Still further proof of the origin of the coals *in situ*, that is, where they now occur, is found in the logs of *Sigillaria* and *Calamites still standing erect in the places of their growth* (Figs. 439–441). There are many of these logs in superposed tiers, Logan reporting seventy-one such exposed in Division 4 alone (see also page 738). These standing logs have been admired by all geologists since Richard Brown discovered them in 1829 and the drawings of them by Logan, Lyell, and Dawson have been repeated in most text-books on Geology. They are of all lengths up to 25 feet, and some of them reach 4 feet in diameter. From their evidence we may agree with Lyell that what he saw in

1842 at the Joggins proved the growth *in situ* origin of these coal beds. Similar erect fossil trees are also known in England and France (see Fig. 442).

Coals of Drifted Plant Origin. — It is probable that the little coal basin of Commentry and other small coal fields in central France owe their coal beds largely or entirely to drift origin in fresh-water lakes.

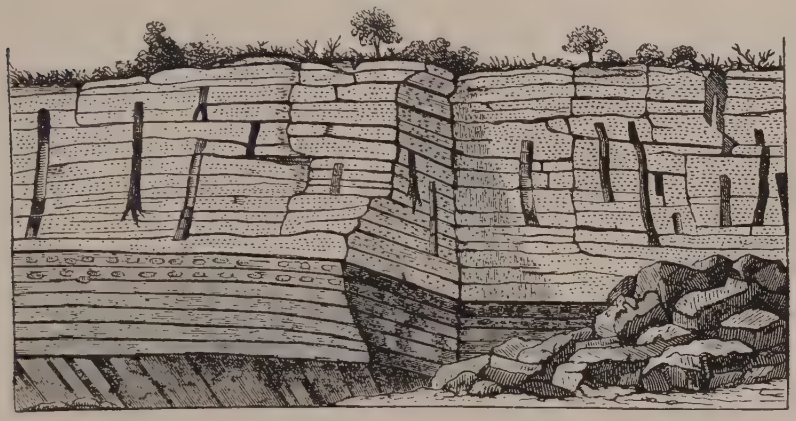


Fig. 442. — Vertical trees in the Coal Measures sandstone, St.-Étienne, France. From Credner's *Elemente der Geologie.*

Thickness of Coal Beds. — Coal beds vary in thickness from a mere film up to more than 80 feet and locally even to 100 feet. A workable bed must be at least 2 feet thick, and it is very seldom that they are thicker than 8 to 10 feet. The mammoth anthracite bed of Pennsylvania has a thickness of from 50 to 60 feet. The Pittsburgh bed of soft coal has a thickness varying up to 16 feet, with an average of 6 to 10 feet. In the Commentry basin of central France, there is a single coal bed of Lower Permian age that is locally over 80 feet thick. On one side of the basin this coal bed divides into six superposed layers separated from one another by sands and shales; this means that coal accumulated continuously in one area, while adjoining it at the edge of the basin of sedimentation there were six periods of sand inflow and deposit, each one of which was followed by one of peat storage. Toward the center of the basin sedimentation gradually ceased, and therefore the marginal separation zones of rock pinch out in that direction.

Résumé of Coal Occurrence in Nature. — As a rule, coal beds occur between coarse sediments, that is, are interbedded with sandstones and shales, and there is in the sections a more or less complete absence of marine strata and animals. Limestones may

be completely absent, and when they are interbedded with the coaly shales are thin and devoid of undoubted marine organisms. Coal beds are known to lie directly on marine limestones (crinidal in Ohio and Pennsylvania), but still there are no marine fossils even in the very basal layers of such coals. In other words, there is no transition from a pure marine fauna directly into a coal bed. Impure limestones are, however, not uncommonly seen to overlie the coal directly (Ames limestone on 18 inches of pure coal in Allegheny, Pennsylvania, Fig. 443), but the contacts are sharp and there is no transition from the coal. The roofing shales of the coals

Fig. 443. — Coal bed about 2 feet thick, directly overlain by marine limestone (Ames). Corner Woodlawn Avenue and Beaver Street, Allegheny, Pennsylvania.

generally abound in fine fern fronds, but occasionally there are very impure coaly covers that contain phosphatic-shelled brachiopods, or even sparse dwarfed marine faunas (Seville, Illinois). In all such cases these are the basal beds of the invading sea, whose water may or may not have churned up the soft peaty material and then redeposited it as a bituminous mud, along with the enclosed shells.

In the great majority of cases coals are underlain by an underclay that is usually unstratified and filled with the roots and root-

lets of plants; in other cases the roots are completely absent though such clays usually have a vertical fracture with some short and slender upright pipes still preserved, which are the casts of once existing roots. These underclays sometimes have the rooted trunks of the former forest still *in situ*, as in the Parkfield colliery, England (see Fig. 444). Underclays therefore are either old soils or the clayey bottoms of the marshes. These soils may be sandy, but are more often true aluminous clays and are then called *fireclays*. They are described at the end of this chapter.

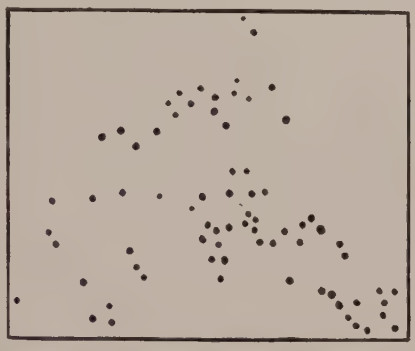


Fig. 444. — A quarter acre of underclay in the Parkfield colliery, England, showing in diagram seventy-three stumps in their position of growth.

Conclusions Regarding the Origin of Coal. — We may conclude that coal beds, as a rule, are formed naturally in the place of their occurrence, either in fresh- or salt-water marshes. The coals of fresh-water marshes are chiefly due to growth *in situ* on river deltas, as are those of the Joggins, or rarely they may be of drifted material in lakes, like those of Commentry. These are the *limnetic coals* (from the Greek word meaning *living in a fresh-water marsh*); they are of small areal extent and of common occurrence in the Permian. Coals were also formed *in situ* on the borders of the epeiric seas or on continental shelves by plants that grew in salt-water marshes whose waters were at first brackish but eventually became fresh. These are the *paralic coals* (meaning *growing by the sea*), often of wide areal extent; they embrace essentially those of Pennsylvanian time. The great purity of many coals is further evidence of their having formed where found, for if made of drifted plants, the water currents bringing the latter must of necessity have also carried muds or even sands, which would have been deposited with the organic matter.

Sulphur in Coal. — The amount of sulphur in coals of Pennsylvanian age is very variable, from a trace to nearly 9 per cent. The average amount in ten anthracite coals from eastern Pennsylvania is 0.6 per cent (0.4–1.0); in seventy-seven bituminous coals from the western part of the same state it is 1.4 per cent (0.4–5.8); in twenty-four soft coals from Ohio it is 2.2 per cent (0.4–6.3); and in the Indiana-Illinois coals, nineteen samples averaged a little over 2.0 per cent (0.3–4). The anthracite coals of Pennsylvania and the bituminous ones of the

Joggins field appear to be wholly of fresh-water origin, since no marine fossils are known in the associated strata, and they have the smallest amount of sulphur. All the other coals are interbedded with strata having more or less of marine faunas, and as these coals are of marshes that were often somewhat under the sea-water, where the sulphur-making bacteria were most abundant, the sulphur content is accordingly far greater. Hydrogen sulphide is found in great abundance in peat beds to which sea-water has access, according to C. A. Davis, and is seldom found in peat formed under fresh water.

Pennsylvanian Coal Fields of America

The oldest coal fields in America, of which there are six (Acadian, Rhode Island, Appalachian, Michigan, Eastern Interior, Western Interior), occupy an area estimated at over 252,000 square miles, a total considerably greater than that of any other continent in the world (see map, Fig. 438). China has the next largest area, in amount somewhat less than that in the United States. Russia has 27,000 square miles; New South Wales, Australia, 16,500; Great Britain, 9000; Germany, 3600; and France, 1800.

1. **Acadian Coal Field.** — The productive area of this coal basin lies on both sides of the Bay of Fundy, along the south shore of Northumberland Strait, and in Cape Breton, and is estimated at about 18,000 square miles. The eastern rim of the basin is in southwestern Newfoundland, where coal beds occur, some of which appear to be valuable. The thickness of the series rises to 13,000 feet and it is somewhat folded.

2. **Rhode Island Coal Field.** — The smallest coal basin, with an area of but 500 square miles, occurs in Rhode Island, extending a little into Massachusetts. The strata strike north-south, with a total thickness of 12,000 feet, and often rest on formations of Cambrian age. The coal is of fresh-water origin, highly anthracitic, or, rather, graphitic, and because of the small amount of volatile matter in it will not burn unless mixed with another coal. This change has been produced by metamorphism, due to the great deformation during the Appalachian Revolution and to the intrusion of large granitic masses.

3. **Appalachian Coal Field.** — This great field is divided into (a) the *anthracite* field, and (b) the *bituminous* or Appalachian field proper. The anthracite field is confined to eastern Pennsylvania, with a productive area of 484 square miles, limited to synclinal basins striking northeast-southwest. The strata of the adjacent anticlines, with their coal beds, have been worn away. This is the most thoroughly developed field.

The Appalachian bituminous field is the second largest and by far the most valuable one in America, extending through nine states, from the northern border of Pennsylvania and eastern Ohio southwestward 850 miles to central Alabama. The basin lies between Appalachia and the Cincinnati uplift, and contains approximately 70,800 square miles, of which about 75 per cent holds workable coal. In general the strata are either gently undulating or essentially horizontal, with the thickness of the formations, as well as the thickness and number of the coal beds, increasing toward the east.

4. **Michigan Coal Field.** — An isolated oval basin is confined to the southern peninsula of Michigan, with an area of approximately 11,000 square miles, whose

strata are thickest in the center of the field. All prospecting for the bituminous coals is done by the drill, because the region is deeply covered by glacial material.

5. Eastern Interior Field. — An isolated coal basin lies to the east of the Ozark mass and west of the Cincinnati uplift, in the states of Indiana, Illinois and western Kentucky. It has an area of 58,000 square miles, of which probably 55 per cent is productive with present methods of mining. In general the coal mined is of the soft bituminous type. The deposits of this basin in the northwest are connected across Missouri and Iowa with the Western Interior field.

6. Western Interior Field. — This is the largest basin, and lies to the north and west of Ozarkia, extending from northern Iowa and Nebraska southwestward 880 miles to central Texas. It also has an eastern extension south of the Ozark mass from central Oklahoma into Arkansas. Here the deposits are also the thickest, are somewhat sharply folded to the north, and form the northern border of the Quachita Mountains. The area of the deposits is about 94,000 square miles, but less than half of it is coal-bearing. In the northern portion the coal is bituminous and fairly uniform in composition. In the southwestern portion the coals vary from soft bituminous to semi-anthracite (Arkansas). To the west the basin is overlain by Permian and later formations.

Composition and Varieties of Coal

General Statement. — On pages 164–169 an explanation is given of how peat accumulates; now we must consider how the plant material comes to be changed into coal. The process is one of *carbonization,* the degree of perfection being due to a slow alteration in the amount of the volatile or organic combustible matter in the course of geologic time. The result is coal in one of its many varieties, depending on the amount of fixed and volatile matters present. The change in the amount of volatile matter is brought about through its loss in the form of gases, chiefly as water vapor and carbon dioxide. This loss of the hydrocarbons seems to be due, in the main, to pressure of the superincumbent strata (load), or that produced by their folding during the time of mountain making. The gases then escape either through the pores or the cracks (joints and cleavage) in the strata, but the success of this escape is again dependent upon the presence of overlying shale beds and their internal construction (grain). In general, the shale beds are impervious to the gases and the circulating ground waters, but when sandy or cleaved through deformation, the chances of escape are greatly enhanced, resulting in anthracite coals that are 95 per cent fixed carbon.

Proofs of the Derivation of Coal from Plants. — We have seen that coals, as a rule, lie upon clays filled with roots, and even upon the floors of the former forests. In the roofing shales of coals are to be seen well-preserved fern fronds and the woody stems of many kinds of plants. Many of these stems are covered with a

film of coal like that of the coal beds. In the coal itself it is common to see thin zones of impure coal, the worthless *bony coal* of miners; this is more or less mixed with clay, the result of coal formation where the marshes were invaded by water currents bringing in mud, and such zones always show plant remains and often very good ones (see Fig. 445). In fact, in almost any coal, even the anthracites, when allowed to weather, we may see plant fibers.

Good specimens of *Lepidodendron*, *Sigillaria*, and *Calamites* may be had along some of the bedding planes of the coal. They occur also in the textureless cannel coal (described on page 792), as in Breckenridge County, Kentucky, where the coal is marked through its whole mass by stems and leaves of *Stigmaria* and *Lepidodendron* rendered distinct by infiltration of sulphuret of iron. Even when nothing of an organic nature is discernible to the unassisted eye, the plant composition of the coals can be made out if suitably prepared thin sections are studied under the microscope. Finally, even the ashes will show vegetable cells.

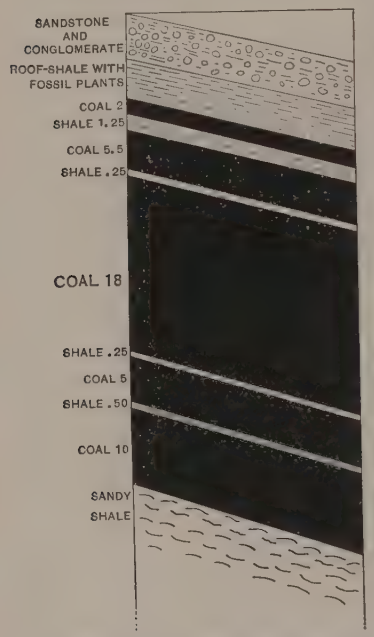


Fig. 445. — Coal bed with zones of shale (bony coal), Prague, Bohemia. Thicknesses given are in inches. From Toula's *Lehrbuch der Geologie*.

Le Conte has truly said that "a perfect gradation may be traced from wood or peat, on the one hand, through brown coal, lignite, bituminous coal, to the most structureless anthracite and graphite, on the other, showing that these are all different terms of the same series. In chemical composition, too, the same unbroken series may be traced. Lastly, the best and most structureless peat, by hydraulic pressure, may be made into a substance having many of the qualities and uses of coal." The formation of peat, a knowledge of which is so necessary to a proper understanding of coal formation, is explained on pages 164–169.

Animal Material in Coals. — Fishes, amphibia, and certain kinds of invertebrate animals are at times found in some abundance in certain coals (Linton, Ohio, Fig. 431) and there can be no doubt that their decomposed remains have yielded considerable carbonaceous material to the peaty or more volatile varieties

Varieties of Coal. — The varieties of coal depend upon the *purity*, the *degree of carbonization*, and the *proportion of fixed and volatile matter*. Following for the most part the definitions of Le Conte, they may be classified as follows:

Varieties Depending upon Purity. — Coal consists both of organic or combustible, and of inorganic or incombustible matter. On burning, the organic combustible matter is consumed, and passes off as gases, chiefly water-vapor and carbon dioxide, while the inorganic incombustible matter is left as ash, composed mainly of silica, carbonate of potash, etc. The relative proportion of combustible matter to ash may vary to any extent, good coals having from 1 to 5 per cent ash. A coal having from 30 to 40 per cent ash is called *bony coal*, and is the valueless refuse of the mines.

Again, all living vegetable tissue contains incombustible matter, which, on burning, is left as ash, the latter amounting to an average of about 1 to 2 per cent. But, as in the process of change from woody tissue to coal much of the organic matter is lost, and the relative amount of ash is thereby increased, we may say that if a coal contains 5 per cent or less ash, it is absolutely pure, that is, its ash comes wholly from the plants from which it was made; but if a coal contains more than 10 per cent ash, it is probably impure, that is, it was mixed with mud or clay at the time of its accumulation.

Varieties Depending upon Degree of Carbonization. — The previously mentioned varieties consist of *pure* and *impure* coals; these consist of *perfect* and *imperfect* coals. We find the vegetable matter, accumulated in different geological periods, in different stages of that peculiar change from woody tissue into peat, and this into coal, called *carbonization*. Brown coal and lignite are examples of such imperfect coal. They are always comparatively modern.

Varieties Depending upon Proportion of Fixed and Volatile Matter. — Coal, even when pure and thoroughly carbonized, still consists of many varieties, having different uses, depending upon the proportion of fixed and volatile matters. These are the *true* varieties of coal.

In pure and perfect coal, then, the combustible matter is part fixed and part volatile. These two kinds of matter may be easily separated by heating the coal to redness in a retort. By this means the volatile matter is driven off and may be collected as tar, oil, etc., in condensers, and as permanent gases in gasometers, and the fixed matter is left in the retort as coke. The proportion of these may vary greatly in different coals, and so affect the uses to which the coal is applied. For example, when the coal consists wholly of fixed carbon, it is called *graphite*. This is not usually considered a variety of coal, because it is not readily combustible, but it is evidently only the *last term of the coal series*.

When the combustible matter of the coal contains 90 to 95 per cent fixed carbon it is called *anthracite*. This is a hard, brilliant variety, with conchoidal fracture and high specific gravity. It burns with almost no flame — the bluish flame of carbonic oxide — and produces much heat.

If the combustible matter contains 80 to 85 per cent fixed carbon and 15 to 20 per cent volatile matter, it becomes *semi-anthracite*, or *semi-humic coal*, of various grades. It should be understood that not all of the volatile matter is combustible and a classification of coals has been made on the basis of the ratio of combustible volatile matter to the fixed carbon. These semi-anthracites are free-, rapid-burning coals, producing a long flame and high temperature, because

they do not cake and clog. They are admirably adapted for many purposes, but especially for the rapid production of steam, and hence are often called *steam coals*. The yellow flame produced by this variety is due to the burning gas of the coal, which is almost wholly a compound of carbon and hydrogen, a hydrocarbon.

If the volatile matter rises to the proportion of 30 to 40 per cent, the coal becomes a typical *humic* (from humus or vegetable mold) coal, which always burns with a strong bright flame, but often cakes or tends to coke. This is perhaps the commonest kind, and may be regarded as typical coal. It is one of the "bituminous coals," but as this word is misleading, coals not being composed of bitumen, humic is preferred.

If the volatile matter approaches or exceeds 50 per cent, a high proportion of which is combustible, a highly fat *humic* or *fusing coal* is formed. This variety is especially adapted to the manufacture of gas and coke.

In addition there are other varieties depending on physical characters. Thus, for example, *cannel coal* (a corruption from "candle coal," so-called because it burns readily with a candle-like flame) is a dense, dry, structureless, lusterless (sapropelic), black type which breaks with a conchoidal fracture. It usually affords the largest proportion of combustible volatile hydrocarbons and is valuable for gas making. When the supply of petroleum and natural gas gives out, these coals will be much used in the making of substitutes for them. Cannel coals occur in Ohio and Indiana and abundantly in eastern Kentucky, and it is in them that fresh-water animal remains at times are plentiful. The cannel coals are thought to owe their fatty nature to the kind of plant material of which they are composed, mainly lycopod spores, and to their conversion into jelly-like masses by bacteria in fresh-water marshes.

Origin of the Varieties of Coal. — The formation of peat from woody tissue, or cellulose, together with the chemical changes involved in the process, has been previously discussed, page 164. It was there shown that the essence of this change consisted in the removal of most of the oxygen with some hydrogen and carbon as gases — water-vapor, marsh gas, and carbon dioxide. The continuing removal of these, especially the last two, from peat tends to raise the percentage of fixed carbon and to convert it into coal of the more humic varieties. The question then arises as to the origin of the anthracite from these more humic coals.

Anthracite differs from bituminous coal in having more fixed carbon and less of the volatile hydrocarbons. It is well known that volatile matter is constantly escaping from coal, and that the gases thus released may become ignited, causing explosions in the mines. If the volatile matters had been constantly escaping during geologic time we should expect all of the oldest coals to be anthracitic, which, however, is far from being true. On the other hand, *anthracite* is almost invariably *found in strata that are more or less folded*, as in the anthracite field of Pennsylvania (see Fig. 446), and when the strata are much deformed the coals are graphitic, as

in Rhode Island. Because of these occurrences it has long been assumed that the mountain-making forces have in some way brought about the change, but as to the exact process geologists are not yet agreed.

We have seen that coal beds are nearly always covered by a shale zone, and when studying the accumulation of petroleum and natural gas we also learned that these pools always occur more or less directly beneath an impervious shale formation. In stratified rocks where coal occurs there is not one single coal bed but many of them, and there are always far more shale zones than coal beds. We have further seen that in the Ohio-Pennsylvania-West Virginia area there are ten horizons of valuable oil in the sand-

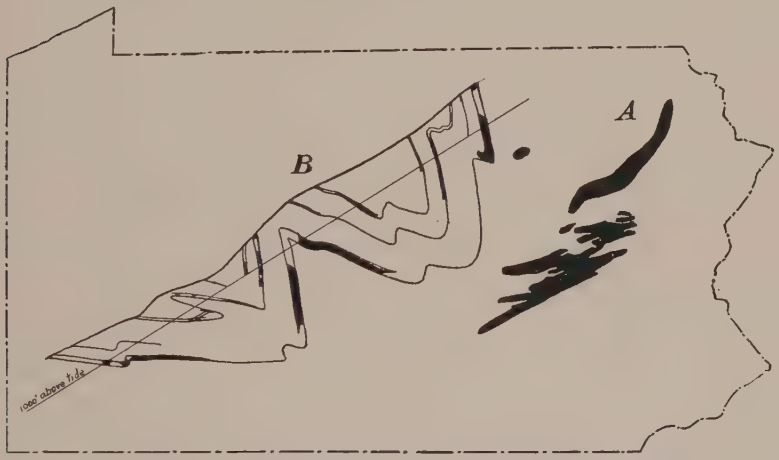


Fig. 446. — *A*, anthracite coal areas in Pennsylvania. *B*, vertical section across the Panther Creek basin in the anthracite region, showing folded nature of the coal beds. U. S. Geol. Surv.

stones. Therefore, we may conclude that *the volatile materials of coal beds and of marine formations are kept, as a rule, from escaping at the surface of the earth by the shale layers.* That volatile materials are constantly escaping at the surface in some localities, however, is proved by the occurrence of burning springs, oil seepages, and asphalt lakes. It should be added here that most of these hydrocarbons are thought to be derived out of the marine strata and not out of the coal beds. In places, a semi-asphaltic material called *albertite,* and looking like bitumen or asphalt, occupies rents in the rocks, instead of constituting layers. A similar substance, called *grahamite,* occurs under like conditions in the Coal Measures of West Virginia. Both are supposed to have been

made from the oxidation of mineral oil, that is, are of animal origin and derived from marine formations.

In mountain-making processes it is well known that shales stretch far more than sandstones and limestones and do not pull apart so readily, forming rents. However, when the deformation is marked, all of the rocks are much cleaved and this cleavage is well shown in the roofing slates of mountainous regions. Further, no oil and gas accumulations of commercial value occur in the mountain belts of ancient origin, but it is in these areas that the anthracite coals are found (see Fig. 446). What more natural inference than that the anthracitic and graphitic coals have lost their volatile hydrocarbons, not so much through the pressure engendered during the time of mountain making as by the cleavage and shattering of the strata above, thus permitting the oil and gas, in the course of time, to escape?

Wastage of Coal in Mining. — The amount of impure coal in nearly every coal bed in the United States varies from 10 to 50 per cent, averaging 25 per cent. At present all of this is thrown away, though much of it could be used for the making of gas for gas engines. Due to faulty mining, bad engineering, the falling of roofs, "squeezes," "creeps," and "crushes," approximately another 25 per cent of the coal present in the mines is never taken out and is thus lost. In other words, about 50 per cent of the coal present is wasted or unused and never to be regained. The wastage in a mine is anywhere from 40 to 70 per cent. "If the wasteful methods of the past are to continue," says I. C. White, "if the flames of 35,000 coke ovens are to continue to make the sky lurid within sight of the city of Pittsburgh, consuming with frightful speed one third of the power and half of the values locked up in these priceless supplies of coking coal, the present century will see the termination of the American industrial supremacy in the iron and steel business of the world."

Value of Coal Mined in the United States. — In 1912 the soft coal mined in the United States amounted to 450,000,000 short tons, valued at $518,000,000. The anthracite output of Pennsylvania for the same year was 75,000,000 tons, valued at $177,000,000. In 1913 three-quarters of a million men were employed in the mining of coal. From 1814 to the end of 1900 the United States had produced 4,470,000,000 short tons of coal, and by the end of 1912 the total had risen to 9,270,000,000 short tons.

Iron-ores and Fire-clays of the Coal Measures

Iron-ores. — In places where coal beds abound one rarely sees red or yellow rocks. The color is generally gray to light greenish, or even whitish, for the sandstones, while the shales, though they may be greenish to black above the coal beds, are usually more or less white clays beneath them. This lack of strong red and yellow colors, which are produced in rocks by ferric oxide (hematite and limonite), is due to the fact that in the presence of organic matter, either in the coals as they were deposited or in the solutions passing downward from them, the ferric iron is reduced to ferrous and then unites with carbon dioxide to form ferrous carbonate. The latter is not a coloring agent and by this change, whose chemical aspect has been previously discussed, page 161, the strata are decolorized except as they may be gray to black from included carbonaceous material. As shown on pages 161 and 170, the ferrous carbonate thus formed, being, like carbonate of lime, soluble in water containing carbon dioxide, may be removed in solution, leached out and concentrated elsewhere. By passing into shallow bodies of standing water the carbon dioxide might escape, the iron be re-oxidized by the aid of the iron bacteria and precipitate as hydrated ferric oxide (limonite), forming the so-called *bog iron-ore.* But in the presence of abundant organic matter, such as the swamps and marshes of the Carboniferous time possessed, this re-oxidation was prevented and the iron concentrated and deposited as the ferrous carbonate. Sometimes the iron-ore was mixed with more or less clay from muddy water and this variety is known as *clay iron-stone;* in other cases it was more or less mingled with black peaty matter, in those swamps where there was prolific vegetation, and this forms the valuable *black-band ore,* which occurs in Ohio and Pennsylvania.

These iron-ores are found in beds of any thickness up to 50 feet, but are usually under 4 feet, and like the coal beds may be repeated many times in a section. They are also often underlain by fire-clays, or the iron-stone concretions occur in the clays.

Fire-clays. — Fire-clays, when impure, are more or less sandy, but are usually aluminous. The aluminous type is the true fire-clay, and is so named because it is capable of resisting heat to a high degree and is much used for making fire bricks to line the insides of blast furnaces. The purest white clays are used for the making of pottery and tiles. The purity of these white clays is due to the presence of carbonic acid in the depositing waters, which takes away the iron and also the particles of feldspar which it decomposes. When some of the feldspar still remains, furnishing soda, potash or lime to act as fluxes, the clays are fusible and are not good fire-clays.

CHAPTER XLIV

THE EARLIEST LAND VERTEBRATES

In the Middle Paleozoic, after the lands had been clothed by plants, there thus became established a habitat capable of sustaining animal life, and destined to be mastered by several stocks of invertebrates and dominated by vertebrates. Among the backboned animals, the first inhabitants of the dry land were the Amphibia, whose short reign lasted only through the Devonian and Mississippian. Then came the longer dominance of the Reptilia, which began their ascendancy in the Pennsylvanian and ruled the lands and even the seas until the close of the Mesozoic. To understand this evolution, it is now necessary to study the organization of these two types of animals.

In Chapter XXXVII are described the structure of fishes, their relationship to one another, and their probable evolution from the invertebrates. Chapter XXXIX sets forth how the probable rise of the fishes took place under the stress of arid climates, which brought about the change from the ancestral marine half-vertebrates into air-breathing fishes. It is immaterial to our further study of the vertebrates whether or not this evolution took place exactly as there described; the fact remains that the oldest known vertebrates occur in estuarine deposits or in those of fresh water, and not in normal marine sediments. Further, air-breathing fishes occur only in fresh-water deposits of Devonian and later time, and in none of the seas and oceans of the present time do air-breathing animals exist, other than those that have come from land-living ancestors, such as the porpoises, whales, and seals. This evidence is clearly indicative that lungs did not originate in the sea. The only possible place, then, where they could have arisen was in waters of an evanescent character, that is, in streams and lakes which periodically dried up under a semiarid climate. The lung-fishes were still animals distinctly habituated to the water, but prophetic of the coming of higher vertebrates, and in the present chapter this further evolution will be traced. Before doing so, however, it will be necessary to understand the structure of the living Amphibia and their developmental stages from the

egg to the adult. Thomson says that amphibians are those vertebrates which made the transition from aquatic to terrestrial life, but almost all have lagged near the water. In many ways they are more closely related to the lung-fishes than they are to higher vertebrates. After the amphibians the next step will be to learn the organization of some of the living reptiles, and with this general information about both it will be easier to understand the more primitive Amphibia and Reptilia of later Paleozoic times.

Amphibia, Living and Fossil

Amphibia differ from fishes in having legs and not fins, each leg bearing fingers or toes. Nearly all of them breathe by gills when very young and may retain these organs throughout life; lungs

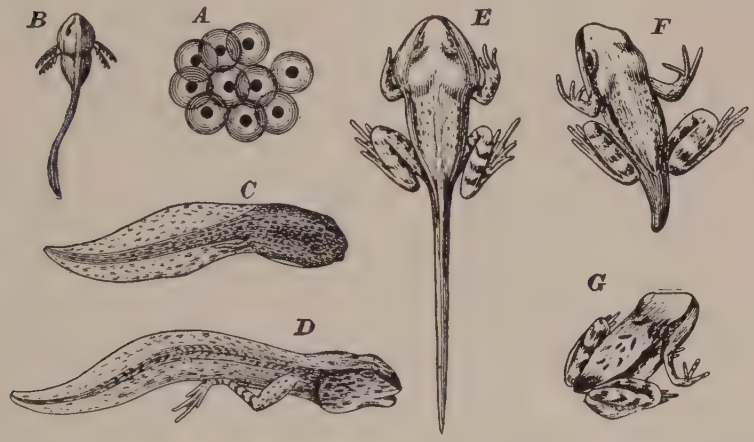


Fig. 447. — Development of the frog (*Rana temporaria*). *A*, eggs, greatly enlarged; *B*, tadpole or polliwog, with two pairs of gills; *C*, tadpole with first indication of hind legs; *D*, older tadpole; *E*, tadpole with both pairs of legs free; *F*, *G*, stages in which the tail is resorbed. Redrawn from Leuckart's wall charts.

are, however, nearly always present in the adult, although among the salamanders they may be reduced to vestiges or completely suppressed (see Pl. 27, Figs. 1–4).

Living Amphibia. — There are about nine hundred forms of living Amphibia, most of which are of the frog kind (Fig. 447). Frogs, toads, newts, sirens, mud-puppies and land salamanders are types of living amphibians (Pl. 27). All are cold-blooded animals. The class name Amphibia, which means *living a double life*, was given them because many live both on the land and in the fresh water. Others, however, live entirely in the water. and, as a rule, all

amphibians in their younger stages are wholly restricted to this element.

The sexes are always separate and in the great majority of species the small eggs are fertilized in the water and develop there without further care from the parents. The development is, therefore, very much the same as in the fishes and very unlike that of the higher vertebrates. The eggs of frogs and toads, for example, develop into little animals commonly known as tadpoles or polliwogs, with a more or less large and rounded head and body terminating in a long and very flexible tail, which they wriggle in swimming, as do the fishes (see Fig. 447). These tadpoles have gills which at first project from the sides of the head, but are later covered by an operculum. In about two months they attain a stage which is the equivalent of the lung-fishes. They then undergo a marked metamorphosis, the hind legs appearing first and later the front pair, which are hidden under the operculum. The long tail shortens through internal absorption and the gills are also absorbed or drop off. The lungs then appear, and for a time the young creatures are fully amphibious, breathing water through their gills and extracting the free oxygen from it, and also taking in air through the lungs; but soon the small frogs or toads take to the land and breathe air only (see Fig. 447). In those forms that remain permanently in the water the transformation is not so great, and some of them resemble fishes in bodily form throughout life, among these being the so-called hellbenders and mud-puppies common to the rivers of the Ohio and Mississippi valleys (see Pl. 27, Fig. 1).

Respiration. — All Amphibia in their youth are provided with two or three pairs of external gills or internal ones with external gill-clefts, soft feathery outgrowths situated at the back part of the head and rich in blood-vessels (see Pl. 27, Figs. 1–3). Such gills are also present in the lung-fishes, and in the sirens and mud-puppies they may persist throughout life, though this condition is rather exceptional. In the salamanders of the land, and in all of the tailless Amphibia (frogs, etc.), the gills disappear and adult respiration is carried on wholly by lungs, as in the higher vertebrates. While the gills are present, the air passages to the lungs through the nose do not open into the mouth, but assume this position as soon as the gills vanish and the lungs become functional. The air is then taken in through the nasal openings and in the frogs is forced into the lungs in a swallowing manner. Many of the Amphibia can live a long time without food, and in the colder

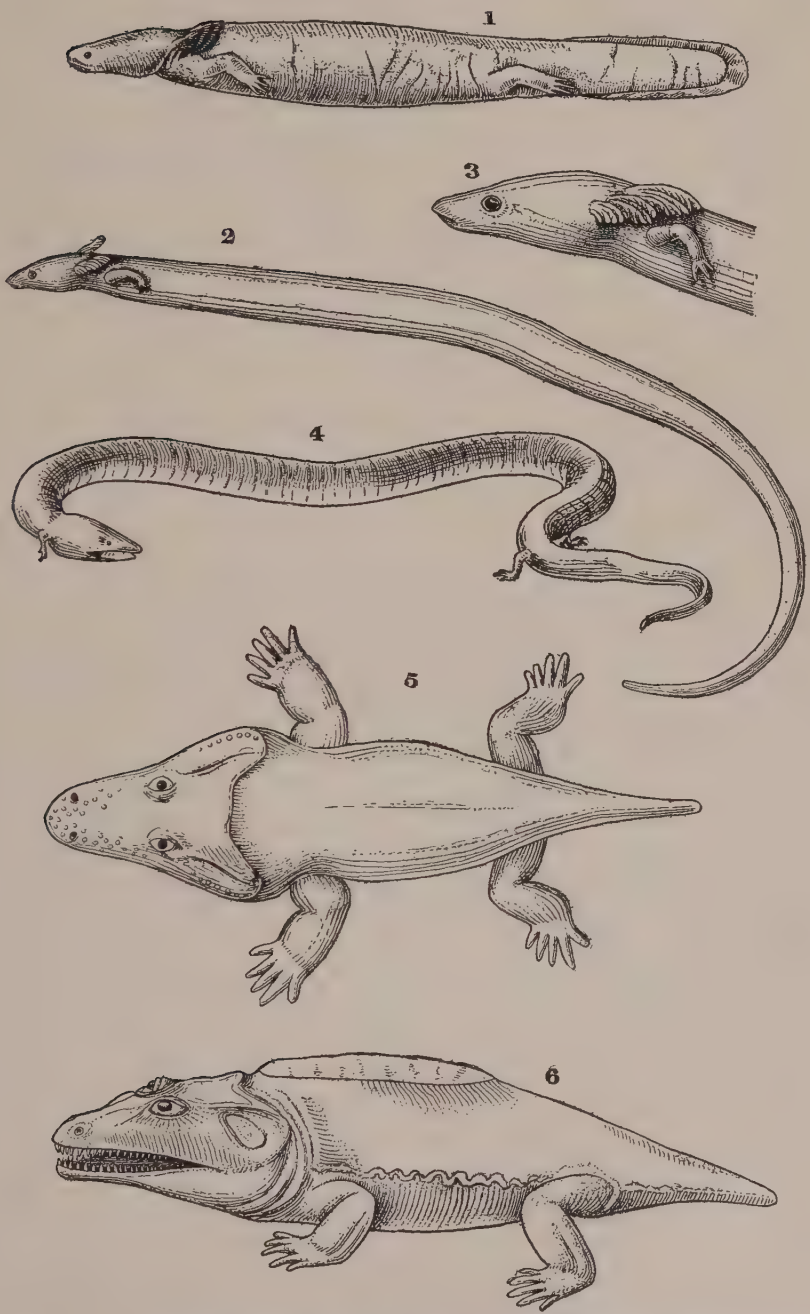


Plate 27. — Amphibia. Living tailed Urodela (1–4) and Permian stegocephalians (5, 6). 1, mud-puppy; 2, 3, mud eel or siren; 4, *Amphiuma*, which has both gills and lungs. British Museum Guide Book, and after Williston. See Appendix B.

countries all the land forms hibernate through the winter in the mud at the bottom of streams and ponds, breathing during this time only through the skin.

Hearing. — In none of the fishes are there functional ears, though there are internal ones; in the amphibians, however, there are distinct organs of hearing. These are best seen in the frogs, where the tympanic membrane of the ear-drum is a more or less large, circular disc embedded in the outer skin on the sides of the head. The cavity behind the disc, or drum, connects with the back part of the mouth by a tube known as the Eustachian tube, which is also present in all of the higher vertebrates.

Classification. — The living forms are divided into two subclasses on the basis of their body form: when tailless in the adult stage, they are called *Anura* (without a tail, see Fig. 447), while the primitive forms retaining the tail are called *Urodela* (having a distinct tail, see Pl. 27).

The Anura include the frogs and toads so commonly known. They always have four legs, the hind pair of which are long and powerful, and the adults are without external gills or gill-clefts. They are almost cosmopolitan, occurring in all countries except the cold polar regions. This subclass is of comparatively modern origin and but a single fossil form is known in the Comanchian, though in the Tertiary strata they occur far more frequently. They are the most diversified of living Amphibia, and, as they are also the most specialized, are not of particular interest in Historical Geology.

The Urodela or tailed Amphibia are of far more significance in this connection, and even though fossil forms are not known older than the Comanchian, the subclass must have had its origin in the Paleozoic Stegocephalia, which will soon be described. The Urodela, now practically restricted to the temperate parts of the northern hemisphere, are amphibians which as adults (salamanders, tritons, sirens, mud-puppies and axolotls) are often strikingly fish-like in appearance (see Pl. 27, Fig. 1). In the mud-puppies and axolotls there is an unpaired fin on the dorsal side, continuing around the diphycercal tail and along the posterior part of the ventral side, as in the lung-fishes. However, this fin does not have skeletal or bony rays, as in the fishes. Even though the Urodela are fish-like in appearance, they are readily distinguished by the fact that their paired appendages are not fins but fully developed legs, though small and weak, with all of the essential skeletal characteristics of the limbs of the higher vertebrates (study Pl. 27, Figs. 1–4). As a rule, there are two pairs of these

limbs, the front or pectoral, and the hind or pelvic. In some forms, however, only the anterior pair is present, the posterior one having been lost, and in a few species all of the limbs are absent, these latter being the burrowing, worm-like Cæcilians of tropical lands. The number of toes on each foot varies between five, the usual number, and two. Some forms, like the land salamanders, when matured may live wholly on the land and lose all trace of the gills, while others, such as the mud-puppies, remain in the water and preserve the gills throughout life. The Japanese and Chinese giant mud-puppy is the largest of all Urodela, attaining a length of 5 feet. One individual lived in captivity for over fifty years.

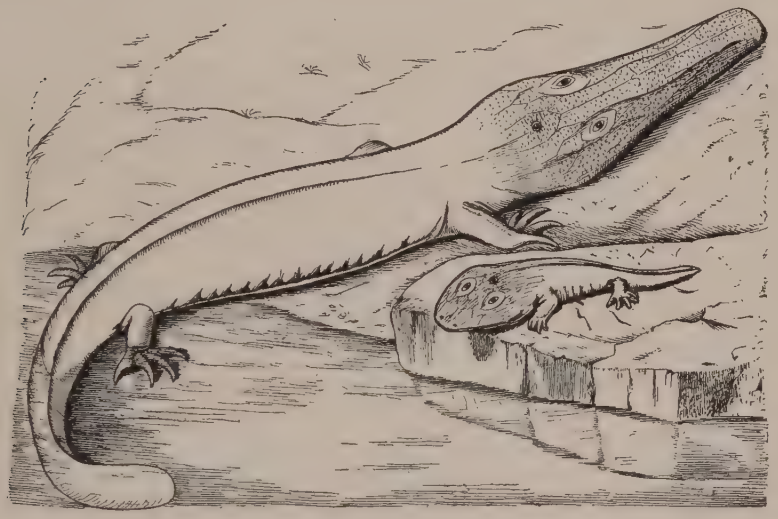


Fig. 448. — One of the larger Stegocephalia (*Archegosaurus*), 5 feet long, with a heavily armored skull; and a small tadpole-like form (*Branchiosaurus*), 6 inches long, whose entire ventral surface bears scales. Note the third or pineal eye. Lower Permian of Germany. From Museum Guide of the University of Tübingen.

Paleozoic Amphibia. — The first trace of an amphibian is a foot impression from the Upper Devonian (page 711 and Fig. 420), and skeletons are not known until Pennsylvanian times. These skeletons represent many kinds of salamanders or crocodile-like amphibians and are most common in America and Europe, ranging in size from less than an inch long to about 8 feet (Fig. 448, and Pl. 27, Figs. 5, 6). A tail was invariably present, and in most cases two pairs of limbs, though snake-like forms are also known (see Fig. 431). They are called *Stegocephalia*, a term which means covered

or mailed head and has reference to the fact that the upper surface of the skull was roofed over by more or less thick dermal bones which were often much sculptured. They are also known as the solid-skulled and armored Amphibia. The chest was likewise provided with dermal armor, consisting of three large sculptured plates which represented a part of the bones of the pectoral arch of the fishes and the shoulder girdle of higher vertebrates. In other forms the entire body was covered with small overlapping scales, those of the ventral side being the thickest, or the scales were on the ventral side alone. Nearly all living Amphibia, on the contrary, are naked and scales are but rarely present (Cæcilians). Many of the ancient forms have been called *Labyrinthodonts*, because in one group the dentine of the large and conical teeth was much folded in labyrinthine undulations.

The whole stock vanished at the close of Triassic time, but it was out of the Stegocephalia that the reptiles developed, and it is becoming increasingly difficult to distinguish the late Paleozoic reptiles from their stegocephalian ancestors. In other words, evidence is rapidly accumulating to show how this lower class of animals has changed into the higher reptiles, and that these changes had to do with their habitat, since the water-addicted Stegocephalia gave rise to forms that became completely adapted to the dry land. These later animals laid their eggs on the land to develop in the warmth of the sun, as do most of the living reptiles; hence the amphibian type of egg had to be modified into the reptilian type (see page 806).

Appearance and Habitat of Stegocephalia. — There are many kinds of stegocephalians known. Some were small and active, with well-developed walking legs and relatively short tails; some were active swimmers, with long tails; others of medium size were thick-set and sluggish in habit, like the crocodiles (Fig. 448); while a few had the appearance of being gigantic, almost legless, tadpoles wriggling about in the water. Their heads were usually broad and flat, with very wide mouths almost the full width of the skull, as in frogs and salamanders; but in some forms the heads were more or less elongated and even pointed, as in crocodiles. The heads of the latter, however, are also broad in the young stages, so that the broad head must be the primitive type. Of the former kind, *Eryops* of the Permian of Texas had a head 2 feet long and 18 inches wide and resembled a huge tadpole with a wide flat head, no neck, a thick heavy body, short legs, and a heavy flattened tail (see *Branchiosaurus*, Fig. 448). As Huxley has said, they

" pottered with much belly and little leg, like Falstaff in his old age, among the coal-forests."

The Stegocephalia lived not only in fresh waters, but, unlike their living descendants, also in brackish ones, and it is thought that some of them may even have lived along the beaches of the Triassic seas. Certain of the small, active types are found in hollow logs of the Pennsylvanian of Nova Scotia, and as thirteen skeletons have been discovered in association with land snails and myriapods, it is thought that they dwelt in trees and died in the places where found. Probably the great majority of Stegocephalia were carnivorous and fed on shell-fish, worms, and other water invertebrates, but more particularly on fishes, reptiles, and small members of their own tribe.

The Third Eye of Stegocephalia. — In all well-preserved stegocephalian skulls the armor or roof bones and those of the true skull were pierced not only by the large lateral orbits in which the paired eyes were situated and by the pair of anterior nasal openings, but also by a single small orifice through the bone over the brain (see Fig. 448). This aperture is of great interest, for in it was situated a third eye known as the *pineal eye*. Such an opening is also found in many fossil and some living reptiles, and while the organ it contains can hardly be regarded as acting like a true eye in living reptiles, its great significance lies in the fact that it is a vestigial organ whose ancestry can be traced back at least to Pennsylvanian time. The rudiments of this eye are present in the brain of all living vertebrates, including man.

In the living New Zealand lizard known as *Sphenodon*, the pineal body shows distinct traces of a retina — the latter being the innermost layer connected with the optic nerve which covers the posterior part of the eyeball — and is the vestige of either a pair of eyes fused into one, or of an unpaired median eye which looked upward. Its origin seems to have been in the lancelets, in which there is but a single median eye.

Sclerotic Ring. — In the cavities of the lateral or true eyes is often preserved a ring of small bones known as the sclerotic bones, which acted like an iris diaphragm for opening or closing the aperture that let the light in upon the retina.

Lower Jaw of Stegocephalia. — The lower jaw in almost all stegocephalians extended the full length of the skull and in consequence the gape of the mouth was very wide. Each half jaw, or ramus, was composed of at least three main pieces, one of which (dentale) bore numerous conical and generally striated teeth arranged in a single series and increasing in size from the front toward the back of the jaws. In some forms there were one or two large, curved, holding teeth in the front of the jaw on each side of the joint (or symphysis) connecting the two rami.

Limbs of Stegocephalia. — In the great majority of Stegocephalia the limbs were well developed but short and stumpy (see Fig. 448 and Pl. 27, Figs. 5, 6). The bones of the front legs were like those of living salamanders in number, form, and disposition, and the hands were provided with four, or rarely five, usually short fingers. The hind limbs were nearly always longer and heavier, and bore five toes, of which either the second or third was the longest. However, it should be noted that a number of stegocephalians are known in the Middle Pennsylvanian of Ohio with snake-like bodies completely devoid of legs and of body armor.

Stegocephalia of the Coal Marshes. — In the Lower Pennsylvanian at Linton, Ohio, underneath "coal No. 6," here a cannel coal, there have been found sixteen species of fishes and thirty-four of stegocephalians. There are a few lizard-like forms up to a foot long, still others with weak limbs, the posterior pair being absent, and ranging in size from 3 to 10 inches, while the most abundant are the snake-like stegocephalians without body scales and permanent gills, attaining to lengths of 4 feet (see Fig. 431). Associated with these are a few land plants, but there is not a trace of a marine animal.

Reptilia, Living and Fossil

In all of the vertebrates so far studied — fishes and amphibians — we have seen that their habitat is either wholly in the water, or that at the very least the small eggs are there laid and fertilized externally, and that the young are also born and spend the days of their youth in this element. All of the higher vertebrates remove themselves more and more from this habitat and none are developed in it directly from the egg. In other words, the reptiles, as a rule, are oviparous, laying *large* eggs like those of birds and provided with a more or less great quantity of food (yolk), and these eggs are fertilized internally by the males before they are laid by the females upon the land, where they hatch under the warmth of the sun. This is the most important and fundamental difference between the lower vertebrates, the fishes and amphibians on the one hand, and the higher vertebrates, the reptiles, birds, and mammals, on the other.

Living Reptiles. — All of the living animals known as turtles and tortoises, lizards and snakes, alligators and crocodiles, and the extinct types, the giant dinosaurs of Mesozoic time and the flying reptiles called pterodactyls, belong to the class Reptilia. The word *reptile* means *creeping* or *crawling* and has reference to an animal that goes on its belly like the snake, or moves with difficulty on short sprawling legs, like the alligator. There are, however, many reptiles that are in no sense creeping and crawling animals,

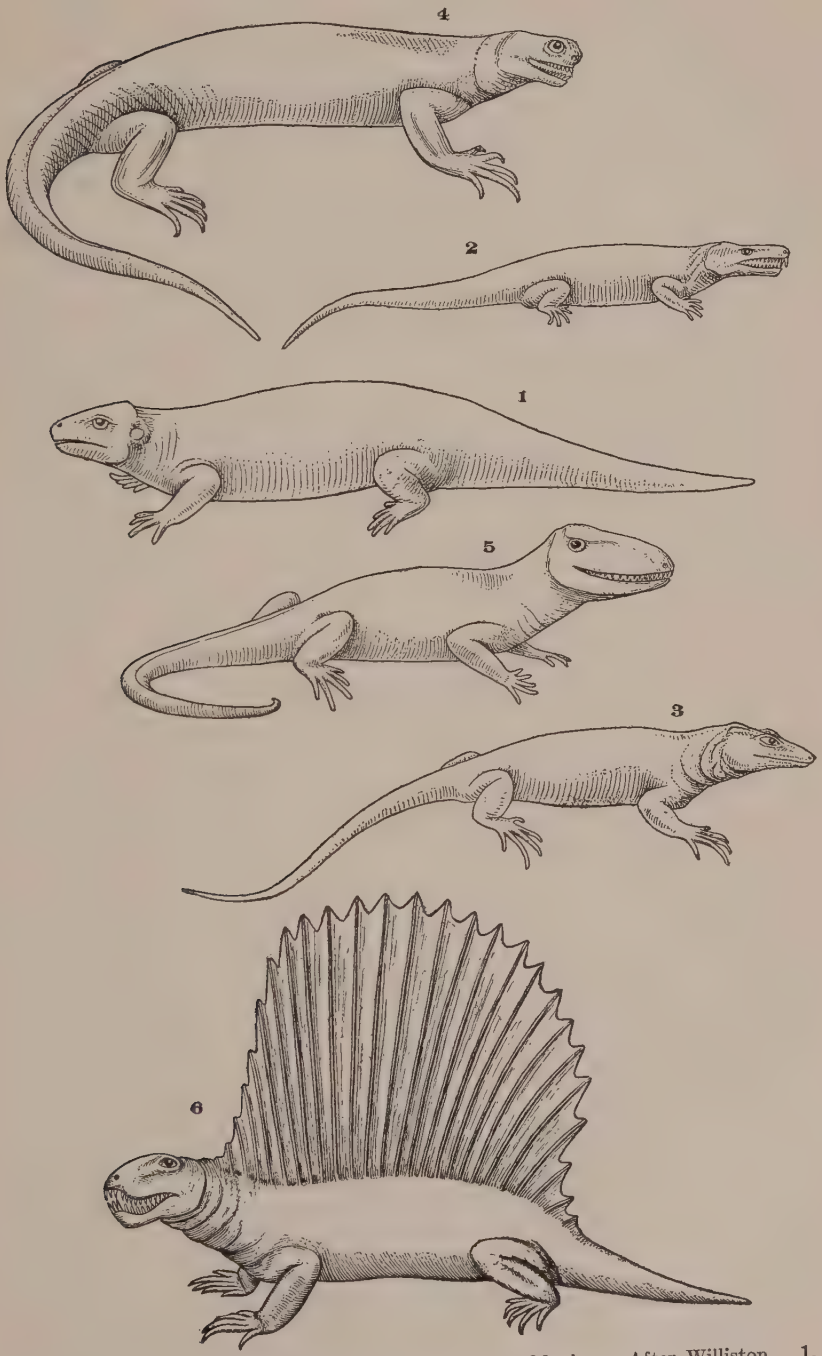


Plate 28. — Permian reptiles from Texas and New Mexico. After Williston. 1, 2, cotylosaurs; 3–6, pelycosaurs. See Appendix B.

as, for instance, many of the fleet-footed lizards, the dinosaurs with their pillar-like legs, and the winged pterodactyls.

All living reptiles are cold-blooded animals like the fishes and amphibians, and their skin is never soft, but always more or less hardened by horny or bony material that occurs more often as scales than as armor plate. Even though many reptiles spend a large part of the time in the water, they are essentially land animals, as they are born on the land and breathe exclusively through lungs. Each animal has a pair of lungs, but in the elongated snakes the left lung is rudimentary and almost lost. In the snakes and in some lizards, legs are either wholly absent or mere vestiges buried in the flesh, and in such reptiles locomotion takes place by means of a wriggling movement either over the ground or through the water. Wherever legs are present, the fingers and toes have claws, a feature that is very rare among Amphibia.

In many of the reptiles eyelids are present, and in most lizards and fossil reptiles the pineal eye is well developed. The organs of smell and hearing are also well developed, but in the reptiles the vibrating, or tympanic, membrane of the ear-drum is no longer external, as in the frogs, but lies in a depression. With the exception of the turtles, nearly all reptiles have teeth; in living forms these are usually pointed and often recurved to serve for the holding of their animal prey. In many fossil forms, however, the teeth were adapted for cutting and more rarely for the mastication of food. In snakes and some lizards the tongue is slender and bifurcated and is protruded in a darting manner. In other reptiles the tongue is flat and immovable, as in crocodiles, being then attached to the floor of the mouth.

Development of Reptiles. — In some living lizards and snakes, and rarely among extinct forms, the females are viviparous, that is, they give birth to fully formed, living young. The great majority of reptiles, however, are oviparous. The eggs resemble those of birds, but are, as a rule, rounder and have a tough, parchment-like, porous covering, or in some cases a calcareous shell. As these eggs are very different in their development from those of fishes and amphibians, they need to be described in more detail.

Since the eggs of reptiles develop on the dry land they must naturally be very different in internal structure from those that hatch in the water. In the latter the embryos have functional gills for use in the water, but in the reptiles a wholly different organ was developed to provide the growing young with the necessary oxygen. Reptile eggs are large and contain a great deal of

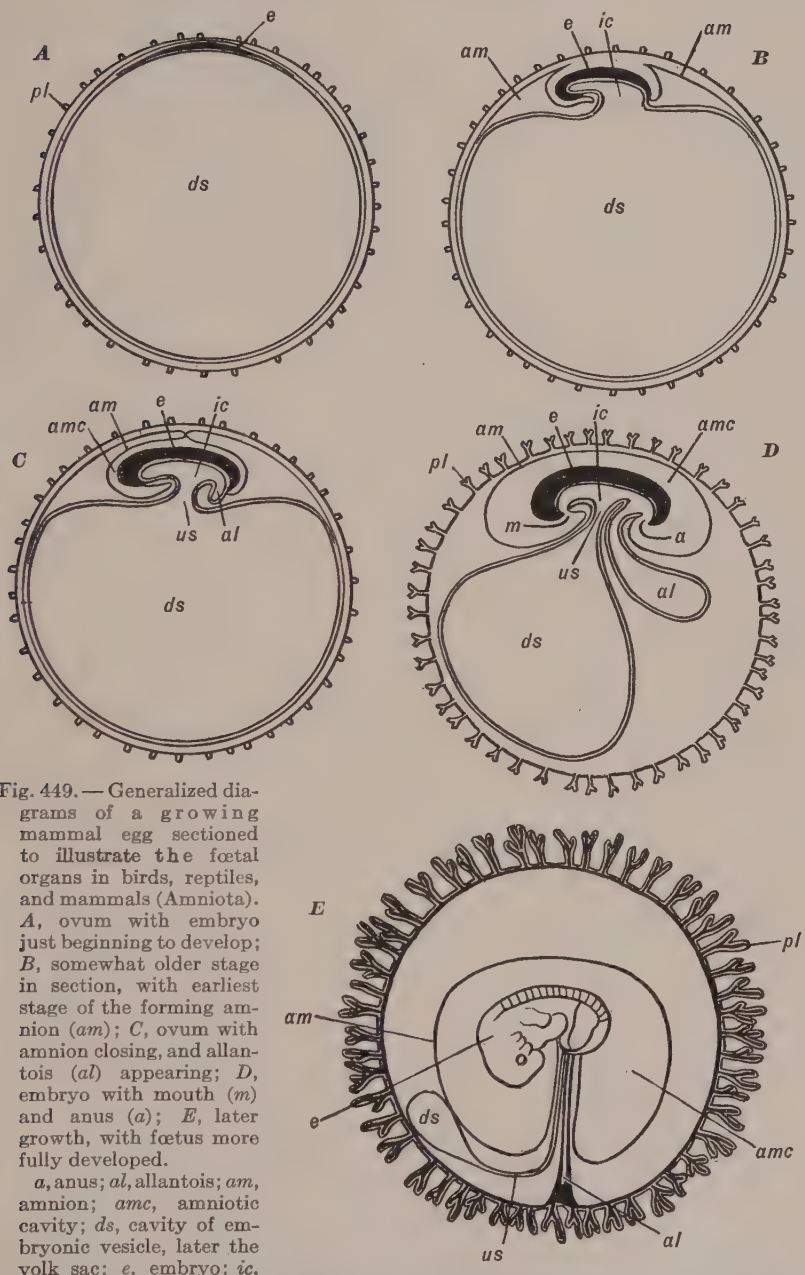


Fig. 449. — Generalized diagrams of a growing mammal egg sectioned to illustrate the fœtal organs in birds, reptiles, and mammals (Amniota). *A*, ovum with embryo just beginning to develop; *B*, somewhat older stage in section, with earliest stage of the forming amnion (*am*); *C*, ovum with amnion closing, and allantois (*al*) appearing; *D*, embryo with mouth (*m*) and anus (*a*); *E*, later growth, with fœtus more fully developed.

a, anus; *al*, allantois; *am*, amnion; *amc*, amniotic cavity; *ds*, cavity of embryonic vesicle, later the yolk sac; *e*, embryo; *ic*, intestinal cavity; *m*, mouth; *pl*, placenta, an organ found only in mammals, formed of the walls of the uterus and embryonal membrane; both are abundantly supplied with blood-vessels, and while there is no direct continuity in the two blood streams, nutrient materials and respiratory gases are exchanged by osmosis; *us*, umbilical stalk. After Kölliker.

yolk, on which the embryo lives and grows. At one pole of the egg lies the fertilized germinal vesicle which develops into the embryo (Fig. 449 *A*). During its earliest growth there is formed at either end of the elongate embryo a two-layered, crescent-shaped fold, called the *amniotic fold*, which arches over the embryo and finally unites to cover it with a protective hood. This latter is the *amnion*, and between it and the embryo there is a shallow cavity containing a watery *amniotic fluid*, bathing and protecting the outer surface of the embryo (Fig. 449 *B*). As the amnion occurs only in the eggs of reptiles, birds, and mammals, these groups are known collectively as the *Amniota*, and the fishes and amphibia, which lack it, are called *Anamnia*, meaning *without the amnion*.

While the amnion is being formed a sac grows out from the hinder end of the embryo, more specifically from the embryonic intestine. This sac, which is of the greatest importance to the animal, is never seen in fishes and amphibians, and is called the *allantois* (Fig. 449 *C*, *D*). It rapidly insinuates itself between the two sides of the amnion, eventually surrounding both embryo and yolk sac. This allantoic sac provides the embryo with the necessary oxygen, passing this and other gases through the porous shell. Finally the embryo breaks through the shell and begins to use its lungs, and the young reptile leads a free life (see Fig. 449 *A*–*E*).

Divisions of the Class Reptilia. — Reptiles are now divided into ten orders, but as most of these originated in the Mesozoic — the Age of Reptiles — we need concern ourselves at this time with the Paleozoic forms only. These are the Theromorpha or mammal-like reptiles.

Paleozoic Reptilia. — It seems probable that the Reptilia arose even earlier than earliest Pennsylvanian time, for in the latter part of this period occurred not only true reptiles but also highly specialized forms. In the Pennsylvanian and older Permian of Texas, Oklahoma, and New Mexico are found many different kinds of primitive Amphibia, and associated with them is even a greater variety of primitive Reptilia, animals that attained a maximum length of 7 feet (see Pl. 28). Their isolated and scattered bones and not infrequently complete skeletons occur in red clays that are devoid of the remains of all marine animals, such strata being regarded as the deposits of a delta or a very wide river valley under an arid climate but completely removed from the influx of the salt water of the sea. In the Wichita region of Texas, Williston has discovered two graveyards replete with entire skeletons, some

of which are 4 feet long, resting in a natural position and piled upon one another to a depth of 2 feet. The creatures had probably died quietly in a stagnant pool of water that dried out annually, causing successive generations of the reptiles to be heaped one upon the other in layers. Even to-day in the same region there are small perennial rivers in wide valleys, and here and there in the permanent pools live fishes, such as catfish and carp, along with frogs and mud-puppies. The modern occurrences suggest the probable conditions under which the late Paleozoic amphibians and reptiles existed.

Most of these late Paleozoic reptiles were plump, sluggish, more or less sprawling animals, basking often on the land in the hot sun, and swimming mainly by the aid of their tails. In many ways they still resembled the stegocephalians, their ancestors, but had a marked tendency toward a reduction in the size of skull and toward loss of body armor. In all the forms the feet terminated in five fingers or toes. Few appear to have been swift of foot, and some bore a curious, very high, dorsal, median crest (Pelycosauria, Pl. 28, Fig. 6). Most of the late Paleozoic forms were fierce looking animals because of their large, recurved, holding teeth, and all of the American representatives seem to have been carnivorous in habit, feeding on armored fishes, armored amphibians, and other reptiles. Others had crushing teeth, indicating a diet of shell-fish and crustaceans.

Cotylosauria were the solid-skulled reptiles (Pl. 28, Figs. 1, 2). They were the most primitive of the group and retained many of the ancestral stegocephalian characters; there was, however, at least one pair of temporal openings (pertaining to the temples of the head) and the teeth were not placed in grooves. The skull was armored with sculptured plates, the pineal eye was large, and a skin armor was sometimes present, all of these features being found in the Paleozoic amphibians. As a rule, the cotylosaurs were small to medium-sized animals, though one African form reached a length of more than 9 feet. In build they were low and stout, they were slow of movement and clumsy in walking, but since they had rather long tails, they swam well. All were carnivorous, though some fed partially on plants. Their geologic range was from late Pennsylvanian to late Triassic, and, while most of them lived in America and Europe, there were some species in South Africa.

Pelycosauria, sometimes called the "fin-backed lizards," were a highly specialized group of Theromorpha (Pl. 28, Figs. 3–6). They were more active and lizard-like than the cotylosaurs, with longer tails, which were not, however, used for swimming. Some were also plump and bore a more or less high dorsal bony crest or "fin," which must have given them a most bizarre appearance. Others, more slender, attained a length of 8 feet. All were fiercely carnivorous land animals, and in certain forms the teeth were enormous, in others somewhat flattened and bearing lateral serrations for the easier cutting of flesh. Pelycosaurs lived

from Upper Pennsylvanian to late Triassic times and were most abundant throughout all of North America, though they also inhabited Europe. None have been found in Africa.

Theriodontia were reptiles which lived only in South Africa during Permian and Triassic times and ranged in size from small forms to those as large as a

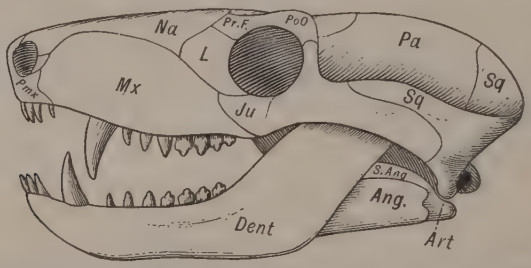


Fig. 450. — A theriodont reptile skull, about 4 inches long, from the Triassic of South Africa, showing primitive mammalian type of teeth. After Broom.

tiger. They are of great interest in Historical Geology as indicating the probable group of reptiles that gave rise to the lowest or egg-laying mammals. Their teeth were differentiated and localized, as in mammals, into incisors, canines, and molars (see Fig. 450).

CHAPTER XLV

THE BEGINNING OF MESOZOIC TIME: THE TRIASSIC PERIOD

Mesozoic Era

To the founders of Geology the Mesozoic rocks were known as the "Secondary" formations, situated above their Primary (Paleozoic and older eras) and beneath their Tertiary divisions. To them the Mesozoic was the middle or medieval time of the earth's history, and they therefore selected a name meaning *medieval life* to express that idea. It is now well known that the Mesozoic formations are far from holding the middle time of geologic history, but the term is perpetuated, though with an amended meaning.

Divisions of Mesozoic Time. — The Mesozoic era, though of very long duration, was only one half as long as the Paleozoic, or even less, but it was twice as long as the Tertiary. At first the era was divided into three periods — the Chalk or Cretaceous, the Oolite or Jurassic, and the New Red sandstone or Triassic; but now the tendency is to recognize four periods, by dividing the great chalk formations into a lower and an upper series, which in America are known respectively as Comanchian and Cretaceous. These four periods, on the basis of organic change, and because of the decided movement that gave rise to the Sierra Nevada Mountains, can be grouped naturally in America into two sub-eras, the Early Mesozoic (Triassic and Jurassic) and Late Mesozoic (Comanchian and Cretaceous).

Characteristic Life of Mesozoic Time. — Louis Agassiz long ago called the Mesozoic the *Age of Reptiles*, because those animals then dominated the world. The Mesozoic Reptilia were very diversified in form and adaptation — small to gigantic, sluggish to agile — but their mentality was always of a low order. Scott tells us: "They filled all the rôles now taken by birds and mammals; they covered the land with gigantic herbivorous and carnivorous forms, they swarmed in the sea, and, as literal dragons, they dominated the air."

Out of the reptiles early in the Triassic arose the small and insignificant reptilian and egg-laying mammals, and from another stock came the reptilian birds, with an abundance of teeth; both

stocks at the close of the Mesozoic era began to modernize into suckling mammals and toothless birds respectively. Among the Paleozoic amphibians, the stegocephalians vanished with the Triassic, and their only living remote descendants are the salamanders and the greatly modified frogs of Comanchian origin.

Of the dominant Paleozoic animals, the trilobites, sea-scorpions (eurypterids), blastids, tetracorals, and graptolites were gone, while the crinids, echinids, and brachiopods were greatly modified and the kinds were not only characteristic of the era, but more like those of the present. The bivalves and gastropods were undergoing great change in the Early Mesozoic, and the culmination of their evolution was attained in Late Mesozoic time. Oysters have been abundant since the Jurassic. The ammonids of the Permian gave rise to a wonderful evolution in the Triassic but were almost exterminated at the close of this period; another rapid evolution took place in the Jurassic, with the Comanchian they began to show decline, and at the close of the Cretaceous they had disappeared. Among the marine invertebrates none were more significant of Mesozoic time than the ammonids.

The floras had also undergone great changes, since all of the more significant spore-bearing plants of the Paleozoic were practically gone and the ancient ferns were changing into the modern stocks. The older seed-bearing plants had given rise to modern conifers and cycads, and the latter dominated the floras of Early Mesozoic time, which is often called the *Age of Cycads* (see Figs. 318, 458). With the Comanchian, the modern flowering plants and insects (beetles, flies, ants, bees, wasps) took their rise, and we may say, in fact, that much of the modern floral and insect world has been established since early in the Cretaceous.

Triassic Period in Europe

The Term Triassic. — In Germany at the opening of the last century, the three-fold stratigraphic nature of the Triassic was already well known, Germany and the Alps being the regions from which most of our knowledge of Triassic time has come. At the base occurs the variegated sandstone member (Bunter, 650–2000 feet) of fresh-water origin, which is overlain by a more or less thick shell limestone (Muschelkalk, 800–1100), made by an epeiric sea that spread northward into Germany from the mediterranean Tethys. This sea again vanished and local coal swamps appeared; then followed variegated continental deposits that are mostly of a red color, along with beds of gypsum and more rarely of salt (Keu-

per, 800–2000). This is the *Germanic phase* and to it Alberti in 1834 gave the name Triassic because of its three-fold development. In England there is no Muschelkalk and all of the Triassic is of continental origin; originally these deposits were known as the New Red sandstone.

In the Alps, and especially in the Tyrolian region, where the deposits are of marine origin, with a wonderful array of fossils, the Germanic classification cannot be applied. Here the Triassic is divided into four members, and as they are of normal marine sediments, this development is spoken of as the *Alpine* or *normal phase.* The latter has become the standard of correlation for the marine strata of this period, while the Germanic phase interprets the land conditions and the diastrophic movements.

Gümbel holds that the area in which was formed the Germanic phase of the Triassic was separated from that of the Alpine or normal marine development by a low mountain tract — the Vindelian mountains — that existed throughout the entire Mesozoic from the Riviera and Sardinia along the Bohemian-Bavarian boundary to the central plateau of France.

Triassic of North America

The Appalachian Revolution (see page 748) not only raised the eastern and southern border of North America into a mountainous tract, but extended the continent to an unknown distance into the Atlantic Ocean as well. Therefore the greater eastern half of the continent remained above the sea for a very long time, certainly to the end of the Jurassic. A further reason why the sea did not spread over this region lies in the fact that another period of elevation set in at the close of the Triassic — the Palisade Disturbance. Hence the geologic record is one of erosion, the making of land forms, and the accumulation of continental deposits in thick series. Along the Pacific border, however, there is a long marine sequence that can be divided in harmony with the European records, and these waters also spread their sediments over much of the entire Rocky Mountains area, but in the main as fresh-water red muds and sandstones. The Triassic of North America is therefore displayed under three different regional sedimentary and faunal phases: (1) Pacific coast normal marine, (2) Rocky Mountains fresh-water, and (3) Atlantic border intermontane continental deposits.

The physical conditions and the absence of the sea in eastern North America in Triassic time were also repeated in South America, most of Africa, and northern Europe and Asia. In other words, the revolution at the close of the Paleozoic

was decidedly positive and extended over the greater part of the earth, leaving most of the continents standing well above sea-level, while the main areas of oceanic overflow were the bordering lands of the Pacific and Tethys. During Middle Triassic time only did Tethys flow widely northward over Europe and lay down the well known epeiric limestones called the Muschelkalk. In nearly all the lands mentioned the climate was semiarid to arid.

Subdivisions of the American Triassic

Marine and continental phases of Europe				American Pacific	Rocky Mountains	American Atlantic	
Triassic	Upper	Bajuvarian / Tirolian	Keuperian	Hosselkus / Swearinger	Vast areas of red beds	Newark series	Brunswick / Lockatong / Stockton-Norristown
	Middle	Dinarian-Franconian		Pit			
	Lower	Scythian-Vosgian		Inyo-Aspen			

Newark Series

Appalachian Revolution. — The Appalachian Mountains, consisting of many ranges that were completed in Permian time, were even then undergoing reduction, and all of the products of erosion were being swept into the oceans. Seemingly the same conditions continued into the Triassic, for no one has yet found among the few fossils of this period in eastern America any that are indicative of the earliest epoch. The fishes, Eastman says, indicate early Upper Triassic, while the plants Stur regards as of the same time. In any event, the Triassic deposits of Nova Scotia (see Fig. 75, page 91) lie upon the nearly peneplained and truncated edges of Paleozoic formations ranging from the Ordovician to the Pennsylvanian. In Pennsylvania and New Jersey the Triassic lies on the planed edges of the Lower Paleozoic. From this evidence we see, further, that the folded structures of Permian time had suffered profoundly from erosion even by the beginning of Newark deposition.

Newark Sedimentation. — The term Newark is taken from Newark, New Jersey, and was proposed by Redfield for the red sandstones found upon the Piedmont Plateau (Fig. 451). Beginning with about Middle Triassic time, the several regions of Newark sedimentation — Nova Scotia, Connecticut, and New Jersey to North Carolina — began to fault along definite lines, and certain narrow but long areas began to subside as troughs, while the adjacent spaces stood firm as unmoved blocks (horsts), or actually rose. In this way the horsts were reëlevated from time to time into more or less high lands, and their eroded material was dragged by the rivers into the subsiding valleys. Such major fault lines

occur along the eastern side of the Connecticut valley and others are known in Maryland, New Jersey, Pennsylvania, and Nova Scotia. In this way the constantly rejuvenated highlands were subjected to quick erosion, and into the sinking valleys on the sides

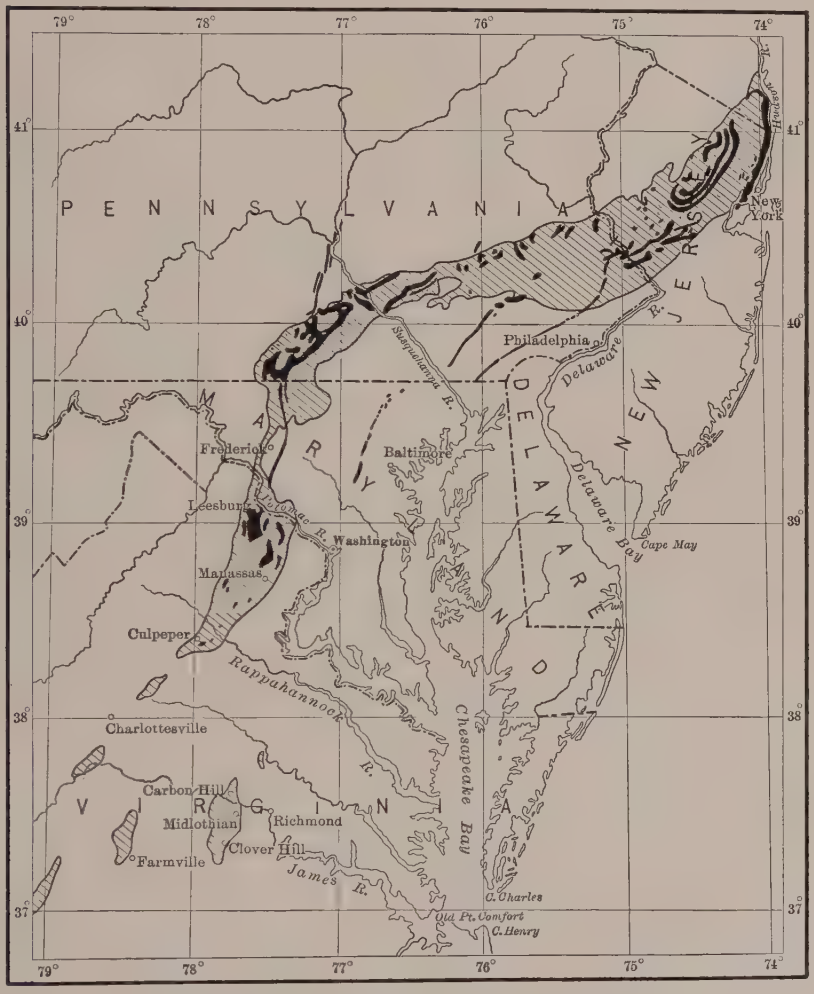


Fig. 451. — Triassic continental deposits (ruled areas) and igneous rocks (solid black) of the Atlantic States. U. S. Geol. Surv.

of the horsts the aggrading rivers brought down vast amounts of sediment, the present Triassic formations. Because of their subsidence the loading troughs also came to lie below the plane of erosion and so were preserved throughout subsequent time. In

the Connecticut valley there are from 10,000 to 13,000 feet of continental deposits (Fig. 452), in New Jersey and in southeastern Pennsylvania the maximum thickness is estimated at 20,000 feet. Southward these deposits thin rapidly, and around Richmond, Virginia, they are about 2500 feet thick, and in North Carolina 3000 feet (Fig. 451).

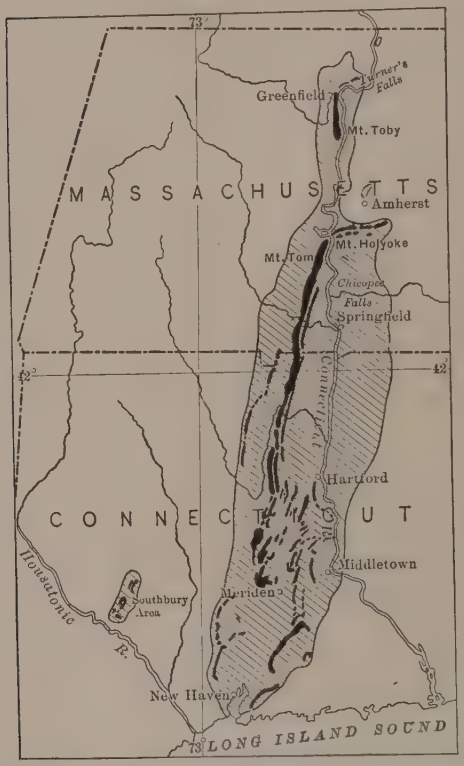


Fig. 452. — Triassic continental deposits (ruled areas) and igneous rocks (solid black) of the Connecticut valley. U. S. Geol. Surv.

The character of the formations and the geological structure of the Newark troughs are analogous to those which exist at the present time in the Great Valley of California and the Sierra Nevadas. There, uplift on the east and downsinking on the west during the later Tertiary have given rise to profound erosion of the uplifted side and transfer of sediment onto the sinking floor. A fault zone separates the Great Valley, the downsunken side of the block, from the Coast Range. The latter also contributes sediment to the valley, but the greater part comes from the crystalline rocks of the Sierras on the east. (Barrell.)

Igneous Material. — In all of the areas from Nova Scotia to North Carolina are found igneous rocks that in the lower strata occur as intruded sheets and dikes of trap (diabase) (Figs. 453, 455) and higher up are extruded sheets of basaltic lavas in thicknesses up to 900 feet (Figs. 451, 452). These are seen to best advantage along the Hudson River of New Jersey, where they make the well known Palisades, whose vertical walls of columnar rock exhibit the edge of a great intruded sheet of diabase. Although the remains of small volcanoes have been found in Connecticut there seem to have been no great ones at this time, and the molten material welled up repeatedly toward the close of Newark time through fissures situated near the great faults, and the lavas were either intruded into the sediments or for the most

part flowed widely throughout the valleys of sedimentation and away from the horsts and rising blocks. Undoubtedly the great subsidences of the sinking valleys fractured the earth's crust deeply enough to let the magmas escape.

Character of Sediments. — From northern Virginia to Nova Scotia the Newark rocks (3300 to 6500 feet thick) are prevailingly red in

Fig. 453. — Palisades of the Hudson River along the New Jersey shore. Note the columnar intrusive diabase above. Photograph by W. H. Rau.

color and consist almost throughout of conglomerates, sandstones, and shales. All of the material is poorly washed or assorted, and in most places is a heterogeneous mass of rock material with the greater part of the conglomerates and the coarser sandstones situated near the fault scarps whence they came. The great bulk of the material is from granitic rocks, showing that the higher lands lay to the east of what is now the Piedmont Plateau (the rolling land east of the Blue Ridge, see page 705), that is, eastern Appalachia, which is made up of Archeozoic and Proterozoic rocks.

Nowhere have the Newark strata yielded a single marine fossil, all of the recovered organisms being those of the land (plants and vertebrates) and of fresh waters (fishes, bivalves). Actual remains of plants and animals are always rare in red deposits, due to the complete oxidation of the sediments during deposition, and

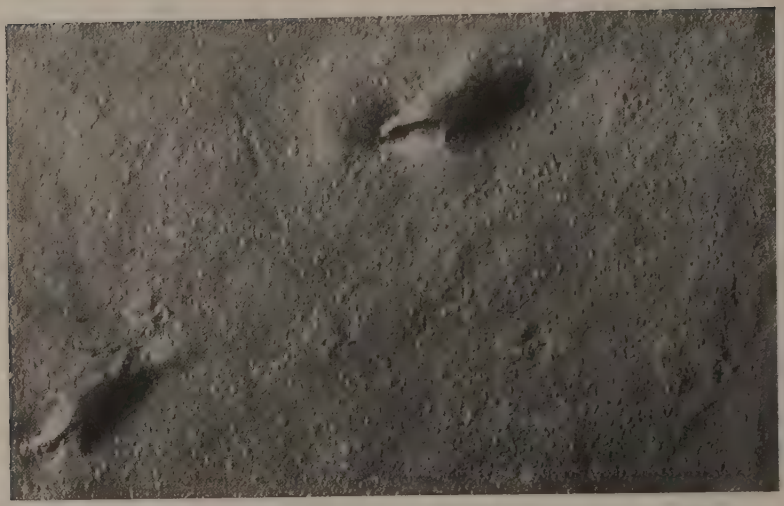


Fig. 454. — Natural casts of rain imprints and dinosaur tracks on a fine-grained sandstone. Yale University Museum.

Fig. 455. — West Rock, New Haven, Conn. Above is the jointed and columnar intrusive trap or diabase, resting on the eastwardly dipping red Triassic sandstone.

the common organic evidence therefore consists of footprints or autographs made by quadrupedal and bipedal terrestrial reptiles (chiefly dinosaurs) (see Figs. 460, 461). The plants and fishes occur in dark to black shales which are evidently the mud deposits of lakes. The sediments themselves are much cross-bedded, abundantly sun-cracked, rain-pitted (Fig. 454), and rippled, with the feldspars undecomposed; they are the erosion material of a high land of crystalline rocks, deposited in a semiarid climate with hot summers and possibly cold winters. (Barrell.)

Connecticut Valley. — In the Connecticut valley the Triassic is readily divisible into three series because of a great medial zone of lava flows. The *upper series* embraces the many quarries about Longmeadow, Massachusetts, and Portland, Hartford, and Middletown, Connecticut, and consists of coarse sandstones, conglomerates and shales, about 3500 feet in thickness, with an abundance of reptilian tracks, chiefly dinosaurian. Very rarely, however, is a skeleton or even a bone of a reptile found, though Hitchcock and Lull have described ninety-eight different kinds of vertebrate tracks. The *middle series* has at the top the posterior lava (trap) sheet, 100 feet thick, beneath which are the posterior shales with land plants and ganoid fishes, attaining a thickness of 1200 feet; then come the main lava flows, 400 to 500 feet thick, followed by the anterior shales from 300 to 1000 feet thick, with plants, fishes, and tracks of dinosaurs; at the base is the anterior lava sheet, 200 to 250 feet thick. The *lower series* consists of coarse granitic sandstones, frequent conglomerates and some shales, and intrusive traps such as those of East and West Rocks at New Haven, with a united thickness of 5000 to 6500 feet. Fossils are very scarce in this lower series.

Fig. 456. — Giant broad-leaved Triassic fern, *Macrotæniopteris magnifolia*. U. S. Geol. Surv.

Coal Beds. — In the Triassic areas of Virginia and North Carolina there is much fine-grained, black, bituminous slate, with decidedly local bituminous coals, and rarely a zone of black-band iron-ore. The coal beds vary in thickness from a few feet to 13 and even 26 feet. Plants are common here, and of these eight are conifers, twenty-three cycads, six rushes, and thirty-five ferns. Among the latter occurs the broad-leaved giant fern (*Macrotæniopteris*, Fig. 456). Very rarely are seen amphibia,

reptiles, and reptilian mammals (*Dromatherium* and *Microconodon*, Fig. 462). These dark deposits with coal swamps, in which Lyell also reports many rushes that still stand vertically, show that the climate of the area of sedimentation was not always and everywhere semiarid, but that locally there were humid climates, with swamps having an abundance of cycads, ferns, and rushes.

Palisade Disturbance. — At the close of the deposition of the Newark series, deformation again set in, and apparently on a considerable scale, from Nova Scotia to South Carolina. Everywhere this new area of deformation lay east of the Appalachian foldings, whose trends the Palisade mountains nevertheless closely followed. The former mountains had been folded and overthrust, due to shortening of the earth's crust, but now the surface was torn apart, resulting in numberless fractures and faults (tensional) of varying magnitude, and moving the strata in each basin into a series of monoclinal blocks, that is, all tilted in the same direction. As a result there were formed chains of block mountains, the Palisade mountains of Dana, probably comparable in height to the Sierra Nevadas of to-day (Fig. 453).

The Palisade mountain system comprised eight to ten independent ranges. They occurred at intervals over a region 1000 miles long, extending from Nova Scotia southwestward to the northern limit of South Carolina. The ranges were from 10 miles to about 350 miles in length and their general course was closely parallel to that of the Appalachian Mountains. The Connecticut River range was 120 miles long, and the Palisade range, extending from southern New York, on the Hudson, into Virginia, was 350 miles long.

The dip of the beds is, with rare exceptions, monoclinal, and mostly between 5° and 25° in angle. In the Connecticut valley, it is *eastward*, in the Palisade belt, *westward*. In two North Carolina belts, the eastern has eastward dip, and the western, westward (Pl. 29). (Dana.)

Marine Triassic of Western North America

Triassic of the Pacific Border in the United States. — Our knowledge of the West Coast or Pacific Triassic is good only for the states of California, Nevada, Idaho, and Oregon, and it is due mainly to the work of Professor J. Perrin Smith. He states that the development of the western Triassic is unusually complete, and in thickness compares favorably with that of any other region of marine sedimentation. The deposits are usually calcareous and fairly thick (about 4000 feet), facts which are in keeping with the view that, as no mountain ranges were developed along the Pacific border at the time of the Appalachian Revolution, there was no high land present to furnish the adjacent seas with much sand and mud (see Pl. 29).

Plate 29. — Triassic paleogeography. Eastern continental strata in black; western, dotted.

The Lower Triassic is about 800 feet thick, the Middle division has about 1000 feet, and the Upper is the thickest, with about 2000 feet. The Middle Triassic faunas are as yet the only ones fully made known, but an estimate based on them indicates that the whole Triassic of this region will yield more than five hundred species, and of these over 70 per cent are ammonids (about ninety genera). All of this, moreover, was true Mesozoic life, for at best there were but few Paleozoic genera then present. The corals (Hexacoralla) made reefs in the Upper Triassic that are known to extend from California into Alaska (60° north latitude), indicating that the waters were warm.

Triassic of British Columbia and Alaska. — Along the Pacific border of British Columbia, from Vancouver north to the Queen Charlotte Islands, the Triassic increases to very great thicknesses (Nicola formation), attaining, according to Dawson, to 13,000 feet. The significant feature, however, is not so much the thickness as the fact that more than nine tenths of the rocks are of volcanic origin. The material is that of submarine eruptions — effusive diabases and trachytes, agglomerates, breccias, and tuffs. With these are interbedded zones of marine sediments, argillites and quartzites, that are thin or even absent to the east, while on Vancouver one such horizon reaches a thickness of 2500 feet.

The Pacific overlap had its widest distribution in the Upper Triassic, for its deposits occur at various points along the western border of North America, and widely over Alaska and Arctic America, with an isolated occurrence in northern Mexico (Zacatecas). These normal marine waters during early Triassic time spread across California and Oregon into Idaho and Utah, and possibly even into central Wyoming. In Middle Triassic time the sea withdrew more and more westerly, so that the Upper Triassic of the Rocky Mountains is all of continental origin.

The marine faunas of the Pacific Triassic were largely indigenous, with decided migrations at times from Asia and the Arctic Ocean by way of the northern Pacific shelf-sea route, and at other times from the western mediterranean (Tethys), seemingly by way of the north shore of Gondwana (see pages 466, 761), and across northern Mexico into the great Californian sea (Walcott, 1894). There appear to have been at least six of these faunal waves, the Asiatic migrations alternating with those of the mediterranean (Smith).

Volcanoes of the West Coast. — The submarine or shelf-sea volcanoes above referred to began their eruptions in Middle Triassic time and seem to have been most active in the early Upper Triassic, when they extended from southern California into Alaska (see Pl. 29). Locally, however, these volcanoes remained active throughout the closing epoch of the Triassic. Near Mt. St. Elias there are about 4000 feet of basalts, followed by the same thickness of Upper

Triassic limestone (Chitistone) and 2500 feet of dark shales. As the Jurassic here rests with a marked unconformity upon these older rocks, it is evident that the Triassic closed with deformation and active erosion throughout the Alaskan region.

About the same time that the volcanoes were active along the Pacific border of North America, much lava flowed out through fissures in the eastern part of this continent (Newark series), as previously stated. Similar lava flows occurred in Argentina and Brazil, but on a more extensive scale, and up to a thickness of 1500 feet (Woodworth). Active volcanoes also existed in New Zealand.

Triassic Red Beds of the Cordilleran Region. — Throughout the Rocky Mountains region, from the Canadian border south into western Texas, and in northern New Mexico and Arizona, occurs

Fig. 457. — Cross-bedded Triassic sandstone (De Chelly), Monument Uplift, Arizona. Photograph by H. E. Gregory.

a series of red or variegated sandy shales and cross-bedded sandstones (Fig. 457), with zones of gypsum sometimes 40 feet thick, that lie over the eroded surfaces of the older formations, and commonly on similar red beds of Permian or Pennsylvanian age. Because of the scarcity of fossils in these red beds, the two series are not yet clearly distinguished in all places. In general, however, it may be said that in the eastern and central portions of the Rocky Mountains area these Triassic formations are thinnest, averaging from 200 to 400 feet thick, and increasing in depth westward to 1000 feet and more. They are all of continental origin.

The fossils of these Upper Triassic red beds are scanty indeed,

but none are of marine origin. Here and there fresh-water bivalves occur (*Unio*) and in many places in the upper portion are thin zones with broken bones, known as bone conglomerates. These bones are in part remains of amphibia (Stegocephalia), but mainly of reptiles of the ancient crocodile type (*Mystriosuchus*, Fig. 458) and of dinosaurs. Characteristic plant remains are almost absent, but nearly everywhere occurs drifted wood that is now agatized; in the Petrified Forest of Arizona, near Flagstaff, this is exceedingly common, and great logs may be seen 120 feet long and with diameters of 8 feet, although the common thickness is from 2 to 4 feet (Fig. 459).

Fig. 458. — Restoration of the Upper Triassic crocodile-like reptile *Mystriosuchus*. The plants are rushes and cycads (upper left-hand corner). After Williston, from his *Water Reptiles*.

Chitistone Disturbance of Alaska. — In Alaska along the Pacific border, from at least Mt. St. Elias to the middle of the Aleutian Peninsula, the Triassic and older formations were thrown into a folded series of mountains at the close of the Triassic. In the lands bordering on the Cook Inlet country, the Triassic strata are, in places, also closely folded and crumpled. Moreover, soon after their folding, they were intruded by felsitic (dense not glassy) igneous rocks, and they are overlain unconformably by Lower Jurassic formations that are far less deformed. In the Mt. St. Elias region the folding seems

to have been less intensive, though here the erosion cycle lasted until about Upper Jurassic time, when the sea came in over the beveled edges of a great thickness of Triassic sedimentaries and volcanics. It seems very probable that the Chitistone mountains extended across the peninsula of Alaska far southward into British Columbia. Finally, a marked break in sedimentation, due either to non-deposition or to erosion of Triassic formations, separates the Jurassic of California from the Triassic, a condition also common to the entire Pacific Coast region. To emphasize this marked diastrophism, the period of orogenic mountain making is here named the *Chitistone Disturbance*, after the thick limestone of the same name so well developed in southeastern Alaska.

Fig. 459. — Three silicified logs of Triassic age in Fossil Forest Park, Arizona. U. S. National Museum.

Life of the Triassic

In the previous pages some mention has been made of the Triassic life of the various American regions, but in this place it is proposed to point out the essentials of the Triassic floras and faunas.

Land Plants. — The Triassic floras are small, as not more than 400 forms are known in all the world, and of these 150 occur in America, with the best representation in Virginia. Practically all the known floras are of Upper Triassic time. Of the Paleozoic genera, nearly all had disappeared. The Triassic flora consisted

essentially of rushes, many of them large; ferns, including tree ferns; and cycads and conifers in many genera (see Figs. 456, 458). The evergreen trees were dominant in the forests and were as tall as the conifer woods of to-day (Fig. 459). In the swamps the rushes made dense brakes like the canes at present, and in general we may say that the vegetation of the Triassic was monotonous. While it was not a luxuriant vegetation, the plants were not dwarfed, as might be expected from the general prevalence of warm semi-arid to desert climates whose existence at that time is proved by the wide-spread red beds and desert sands. Further, there were no marked seasonal changes, as the trees were devoid of annual growth rings, and it is held by botanists that the climate was warm and subtropical. (Knowlton.)

Fig. 460. — Slab of Triassic sandstone, 6 by 3.5 feet, pitted by rain. A large dinosaur (*Steropoides diversus*) walked over the muddy ground before the storm, and a much smaller one (*Argoides minimus*) afterward. Yale University Museum.

Insects. — Our knowledge of Triassic insects is almost a blank, for less than thirty species are known, and of these about two thirds are beetles, a group of animals that arose in this period.

Fresh-water Faunas. — In the Triassic the fresh-water deposits contain *bivalve shells*, and in a broad way we may say that these were not very unlike those of the rivers and lakes of to-day. Of course, the species, and in most cases even the genera, were not the same, but nevertheless the pearl shells (Unios) were abundant. Fresh-water snails, although they arose in the Pennsylvanian, were still rare. The *lung-fishes* were greatly reduced in number, and

the dominant forms were the *ganoids*, with the bony fishes advancing toward our present types.

Land Animals. — The vertebrates of the land were now very varied and of great interest, exhibiting much structural and adaptive progression over their late Paleozoic ancestors. Among the amphibia the *stegocephalians* attained their culmination in number, variety, and size. Progression was, however, especially marked among the Reptilia as a class, and specifically among the active dinosaurs (see Pl. 31). Scott tells us that almost all of the twenty-five orders of Mesozoic reptiles were already represented in the Triassic, though often by comparatively small and rare forms. Their footprints are known in eastern North America in great variety (Figs. 460, 461), but good skeletons are exceedingly rare. In Europe,

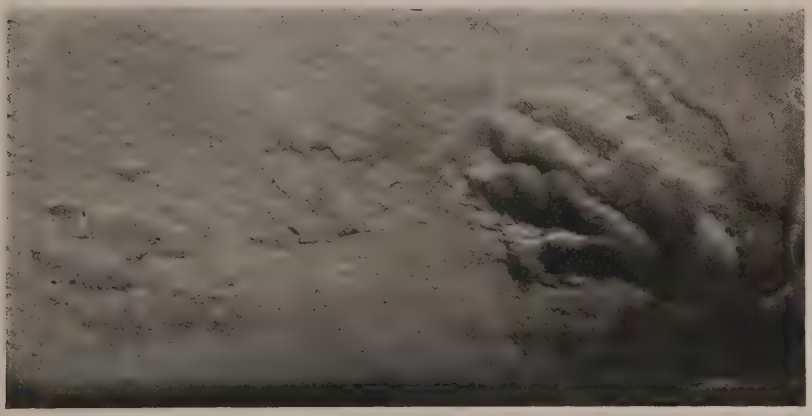


Fig. 461. — Tracks of the largest known Triassic dinosaur (*Otozoum moodii*). Slab 4.5 by 2 feet. Yale University Museum.

on the other hand, their skeletons are more common, and, so far as known, the animals were of the same kinds as those of America. From this and other evidence it appears that the great northern continent Eria (Fig. 434) was still intact and was the land across which the plants and animals of Triassic time readily migrated to and fro. *Crocodile-like reptiles* of the sprawling type (*Mystriosuchus*, Fig. 458) and other active forms (*Aëtosaurus*, Pl. 31, Fig. 9) were common. Genuine *turtles* occur in the Triassic rocks, showing that the group originated in the Permian. No lizards, snakes, or birds are as yet known in rocks of this era.

The *dinosaurs*, however, were the lords of the land, and they were present in great variety and in great size; in fact, some, known by

their footprints only, must have been larger than elephants (Fig. 461). In the Upper Triassic they had become adapted to all the land habitats. Some were herbivorous, others carnivorous; some walked on all fours; others walked occasionally or habitually on two legs, after the manner of birds. The best known American form is the carnivore *Anchisaurus* (Pl. 31, Fig. 6).

Archaic or Reptilian Mammals. — Of greatest interest is the rare occurrence in the Triassic of Virginia (two lower jaws, Fig. 462) and Europe (isolated teeth) of diminutive reptilian mammals. Mammals are the most highly organized animals, but these, their earliest known representatives, were very small and very primitive,

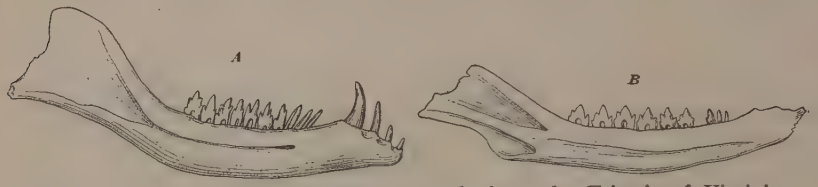


Fig. 462. — Lower jaws of reptilian mammals from the Triassic of Virginia. *A*, *Dromatherium*, × 2; *B*, *Microconodon*, × 3. After H. F. Osborn.

giving little promise of being the future conquerors of the world (Scott). They probably had their rise in the mammal-like reptiles known as the Theriodonta (Fig. 450, the name meaning beast-tooth, and having reference to the resemblance between their teeth and those of carnivorous mammals) which were common in Africa and Europe during the Triassic. The first stock of mammals to arise were the Multituberculata (Fig. 484), so named because the teeth have coned or tuberculated surfaces; these were reptilian, probably egg-laying mammals. Of this stock there are left but a few small specialized and degenerate forms known as the duck-billed mole (*Ornithorhynchus*) and the spiny ant-eater (*Echidna*), which are now living in Australia.

Marine Vertebrates. — In previous chapters we have seen how the fresh-water vertebrates were forced to adapt themselves to the land, and how this habitat was attained only after a very long struggle. Now that the reptiles were firmly established on the land, however, we see them going back again to the water, not only intermittently to the rivers and lakes, but permanently into the seas and oceans, where there was a more certain food supply in abundance than is usually the case on the land. Dolphin-like reptiles, the ichthyosaurs, were present, though still rare (*Shastasaurus* of California), and a stock of long-necked, box-bodied

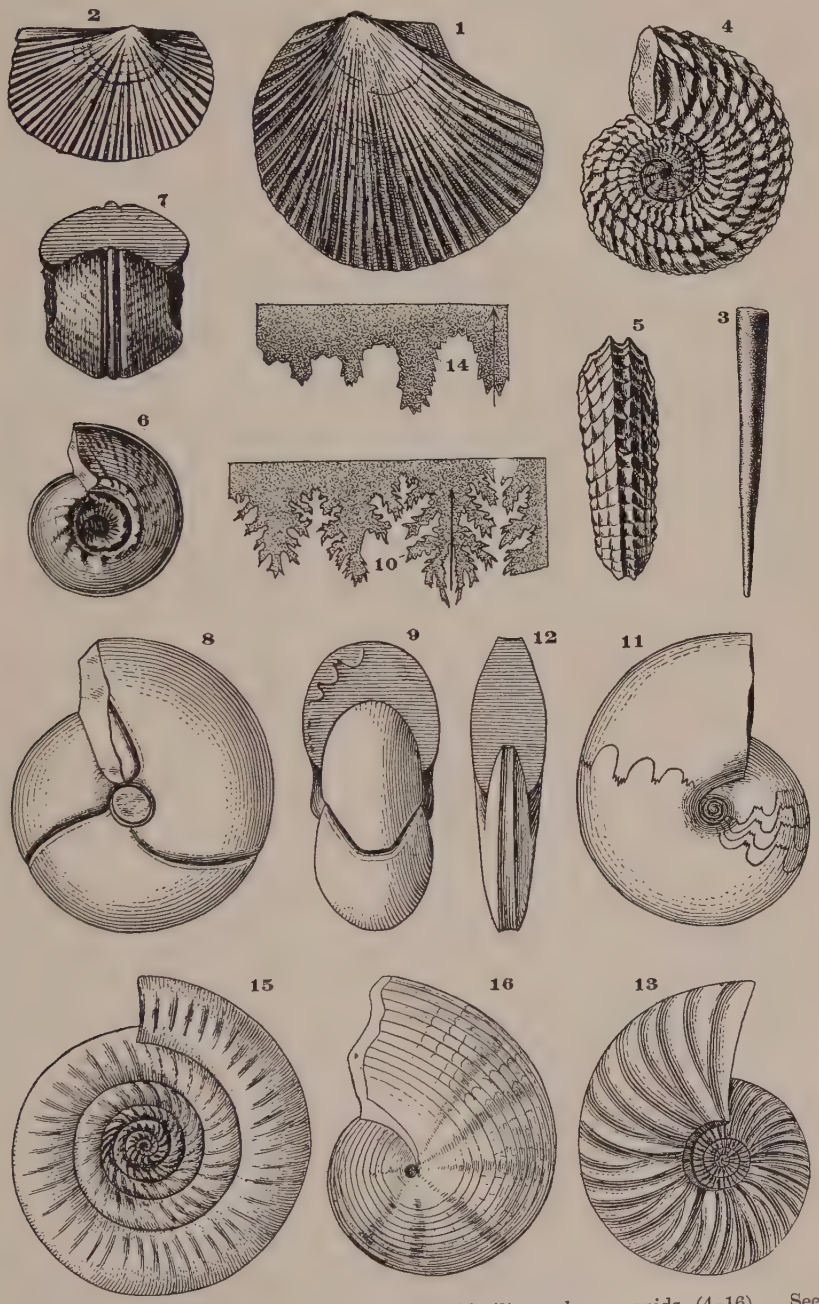


Plate 30. — Triassic bivalves (1, 2), belemnid (3), and ammonids (4–16). See Appendix B.

sea-dragons, the plesiosaurs (*Nothosaurus* of Germany), also had its start at this time, both of which groups became characteristic and abundant in the Jurassic and will be described in Chapter XLVII (see Figs. 469, 471). Here again we see the wonderful extent to which organisms can adapt themselves, for limbs have been changed from walking legs to swimming paddles, and the egg-laying method of rearing the young has been altered to that in which the young are born alive (viviparous development).

Marine Invertebrates. — The seas swarmed with ammonids in great variety (Pl. 30, Figs. 4–16). They were not only the most beautiful and characteristic animals of the Mesozoic seas, but also the highest expression of invertebrate evolution in agility and in predaceous and scavenging ability. Some of the species spread widely throughout the world. The squids originated in the Triassic (Pl. 30, Fig. 3) and were common in the Jurassic. Among the other shelled animals, the bivalves (Pl. 30, Figs. 1, 2) and siphonate gastropods were in the ascendancy. The brachiopods, though still common in Tethys, were very rare in the American Pacific faunas and have remained so up to the present time.

In the Upper Triassic appear the modern reef-building corals (Hexacoralla), which built limestones in Tethys up to 4000 feet thick, while reefs are known elsewhere with many identical species, as in the Himalayas, and in the eastern Pacific from California into Alaska. The modern echinids and lobsters also originated at this time, but were not conspicuous until later. Tethys and the western Pacific were the main centers of marine invertebrate evolution.

A survey of the life of the Triassic, contrasted with that of the Permian, shows that no greater change is recorded in all geologic time. This was the result of the marked physical changes undergone by the earth during the Appalachian Revolution at the close of the Paleozoic, one of the most critical periods in the history of the organic world.

CHAPTER XLVI

DINOSAURS, THE RULERS OF THE MESOZOIC

By Richard Swann Lull

The Mesozoic is truly the Age of Reptiles, but it might equally well be called the Age of Dinosaurs, for these animals were then the rulers of the dry land and the fresh waters. As they were so characteristic of all lands, and particularly of North America, during the Mesozoic, and as they are among the most interesting animals of all time, we must study them in some detail. What reptiles are and how they are related to the amphibia and the still lower vertebrates have been discussed in Chapter XLIV, and this knowledge should make the following account more easily understood.

The reptiles which most nearly paralleled the mammals of to-day were the dinosaurs, taking into consideration range of size, habits, and habitat. As the former were the dominant land animals of the Tertiary, so the latter were indisputably the ruling dynasty of the Mesozoic. In size they ranged from that of a chicken to gigantic monsters probably 80 feet in length. There were two main groups of dinosaurs, one herbivorous, the other carnivorous, both probably evolved from the same stock.

Carnivorous Dinosaurs (see Pls. 31–33). — The carnivorous dinosaurs, to which the name *Theropoda* (meaning *beast-footed*) has been given, were active rapacious forms running upon the hind limbs after the manner of many of the swifter lizards of the present, with hands and feet armed with increasingly powerful claws, and jaws with slightly curved dagger-like teeth, the sharp edges of which were often serrated to add to their efficiency as weapons of offense. So far as our knowledge goes, the carnivores were never defensively armored, though impressions of the actual skin are yet to be discovered; nor were they, with rare exceptions, endowed with horns or other bodily excrescences characteristic of the plant-feeding forms. Throughout their entire evolutionary career they relied for sustenance and defense upon strength or agility and, as in the great cats of to-day, upon power of tooth and claw.

The Theropoda shortly verged into three lines of descent, two of which remained carnivorous and terrestrial in habit, the one a

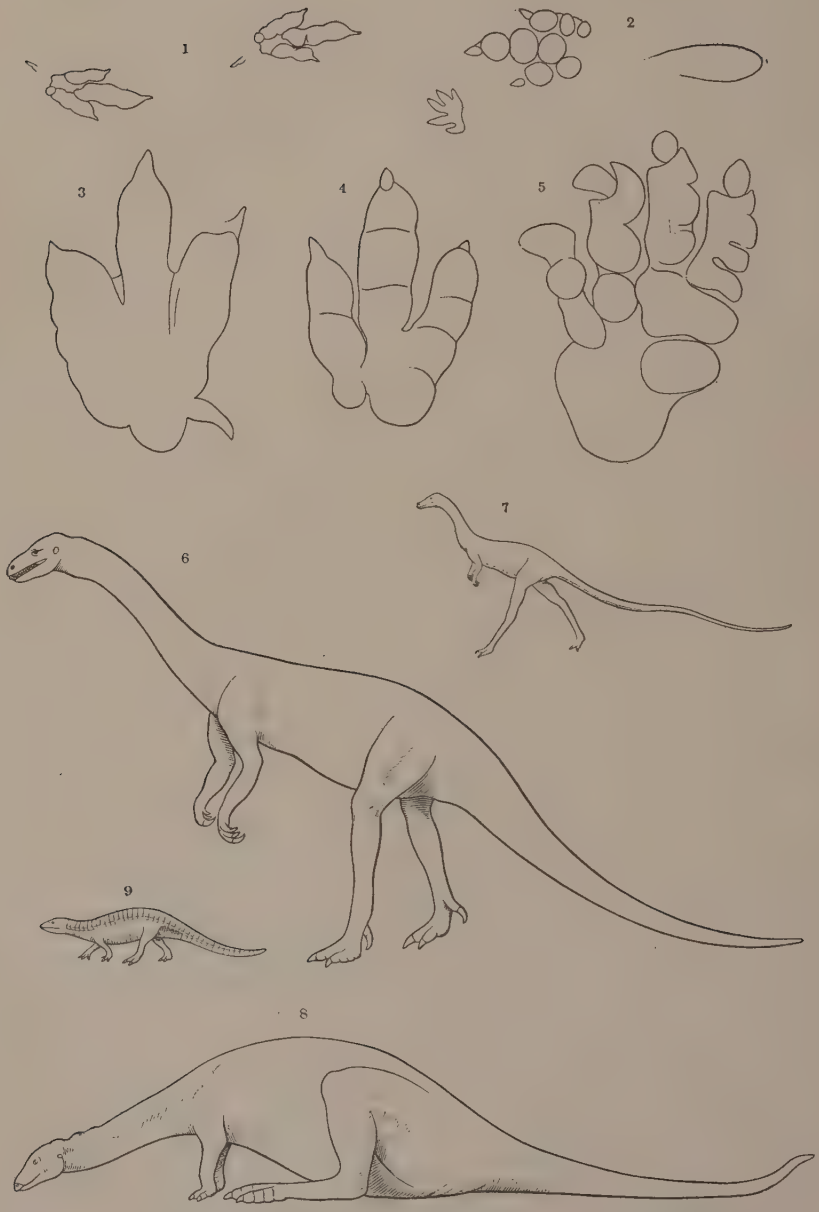


Plate 31. — American Triassic dinosaurs (1–5, footprints; 6, 7, carnivores; 8, herbivore), and a walking, crocodile-like reptile or aëtosaur (9). Restorations by Lull. See Appendix B.

smaller, more agile race preying upon the humbler reptiles, possibly upon the birds (see Pl. 32, Fig. 6), the other growing more and more ponderous as time went on, keeping pace with the increasing stature and armament of the vegetarian hosts. One peculiar feature of their evolution was the arrest of development of the fore limbs, until in the culminating forms they were so absurdly small that one can scarcely conjecture their use (Pl. 31, Fig. 7).

Sauropoda (see Pl. 32). — The third race which evolved from the theropodan stock had a relatively brief career. Its forms, because of increasing bulk, either did not attain the erect bipedal gait or reverted to the quadrupedal posture of their pre-dinosaurian ancestry; and then, the burden of the flesh becoming too great, they forsook the land and became partially if not wholly aquatic in habit. This group, the *Sauropoda* (meaning *reptile-footed*), is represented by several nearly complete specimens, notably by that of the majestic *Brontosaurus* (Pl. 32, Fig. 1), the thunder-saurian, a creature some three-score feet in length and ponderous of body, but with long, tapering neck and tail, as though an elephant were deprived of its normal terminals and provided with those of an enormous snake. The teeth, confined to the forward margins of the jaws, are clearly derivable from those of a carnivore, but blunted and often somewhat spoon-shaped, apparently so ill-fitted for any known type of food as to cause the widest conjecture as to the precise nature of their owner's diet. Flesh being hardly possible, fish has been suggested, but there is nothing among the associated fossils to indicate the amazing quantity which must have been required to supply the sustenance for growth and motive force in a creature whose weight approximated 37 tons! The final inference, therefore, is that some sort of plant life growing in great abundance and easy to secure formed the food, which was not masticated but detached by the claws and teeth and swallowed intact. The presence of smoothly polished stones, foreign to the local rock, which have been found within the ribs of occasional specimens, suggests the existence of a gizzard-like device for the reduction of this inert mass of food.

An elephant weighing 5 tons eats 100 pounds of hay and 25 pounds of grain for his day's ration; but as such food is in a comparatively concentrated form, it would require at least twice this weight of green fodder for an animal of the same size. The largest brontosaur probably weighed 37 tons, and it is estimated that its daily food must have been something like 700 pounds of plants.

But here we must curb our imagination a little and consider another point: the cold-blooded, sluggish reptiles, as we know them to-day, do not waste their energies in rapid movements, or in keeping the temperature of their bodies above

Plate 32. — American Comanchian dinosaurs (1–3, sauropods; 4, predentate; 5, armored; 6, carnivore). Restorations by Lull. See Appendix B.

that of the air, and so by no means require the amount of food needed by more active, warm-blooded animals. Hence these great dinosaurs may, after all, not have been gifted with such ravenous appetites as we fancy. (Lucas.)

The skeleton of one of these creatures is a marvel of mechanical design; the bones of the vertebral column are of the lightest possible construction consistent with strength, the bony material being laid down only where stresses arise and reduced to a minimum at other points. The assembled skeleton reminds one forcibly of a cantilever bridge borne on two massive piers — the limbs — between which the trunk represents the shorter channel span, and the long neck and tail the spans leading to the shores. Over the hips is a ridged anchorage formed by the coalescence of several vertebræ, for not only was this the point of origin of the tendons and sinews supporting the 30 feet of tail, but on occasion the whole forward portion of the body, fore limbs, and neck could be raised clear of the ground after the manner of a bascule bridge. In the refinement of its architecture the vertebral column is essentially Gothic, with arch, pillar, and buttress, and the freedom of design characteristic of the great fabrics of medieval time.

None of the known Sauropoda were small. *Brontosaurus* was of representative size; while another, *Diplodocus*, was lighter in build though long and slender, with the terminal half-score of its 80 feet of length an attenuated whip-lash-like appendage of unknown use (see Pl. 32, Fig. 2). The Sauropoda seem to have inhabited the sluggish waters of an imperfectly drained country, which supported their huge bulk, and supplied the aquatic plants upon which they fed. That they were armorless and defenseless seems certain, though impressions of a coarse integument are sometimes preserved. Their ponderous size, however, must have given them a certain immunity from attack, while their chosen haunts kept them out of competition with their fiercer kin. The western United States has produced the most perfect specimens, but a recent discovery at Tendaguru, German East Africa, has brought to light the most colossal individuals thus far recorded. Of these, perhaps the best known is *Brachiosaurus*, a genus which is also represented in North America. Some of the cervical vertebræ in this form are 3 to 4 feet in length and the total length of the neck has been given as 36 feet. The fore limbs were longer than the hind and the upper arm bone measured 6.5 feet. The tail, on the other hand, was relatively short. While extremely massive in build, the total length of this animal was about that of *Diplodocus*, probably not more than 80 feet, instead of 120 feet as the earlier accounts stated.

Predentate Dinosaurs (see Pls. 32, 33). — The other great dinosaurian race, in contrast to those above discussed, was exclusively plant-feeding throughout its known history, and, as a special adaptation to this form of diet, bore within the mouth a wonderful battery of teeth. The front of the mouth, contrary to that of the Sauropoda, was toothless except in the most primitive forms, but in compensation had a very efficient cropping device in the form of a turtle-like beak for securing the food. In the rear of the jaws, on the other hand, were deep grooves which lodged vertical rows of successional teeth, of which the outermost two or three in each row pushed against their fellows in the opposing jaw, while those lying deeper migrated outward to replace such as were worn out and lost through use. The teeth were few and simple at first, becoming, as time went on, more and more numerous, until in *Trachodon* (Pl. 33, Fig. 6), the terminal member of one line, the dental battery contained no fewer than two thousand teeth. These predentate dinosaurs, so called from the peculiar toothless bone that united the two halves of the lower jaw, soon differentiated into two distinct races, the unarmored bipeds and the armored quadrupeds, while from the latter arose a third, the horned dinosaurs or Ceratopsia.

Bird-footed Dinosaurs. — Of these three types, the unarmored Ornithopoda, or bird-footed dinosaurs, depending for defense largely upon fleetness of foot, were the least specialized, and in their evolution paralleled the carnivores almost precisely (Pl. 32, Fig. 6). Like the latter they were divided into a lesser and a greater race, some being of small proportions, 4 or 5 feet in length, while others reached a length of 40 feet. A fortunate discovery made in Niobrara County, Wyoming, in 1908, brought to light a specimen of *Trachodon* which, because of the marvellous preservation, permits an almost perfect mental reconstruction of the animal. The dinosaur had apparently died where it could be gradually desiccated under the heat of a tropical sun until the skin and much of the flesh and tendons had shrunken down upon the bones. In places the skin is thrown into the finest wrinklings, showing it to have been as thin as that of a python; but in contrast to that of the snake, it bore not scales but tubercles, some rather large, others excessively fine, but showing a distinctive arrangement. There is, however, over the entire body no trace of defensive armor. The curious webbed character of the hand and the presence, in other specimens, of a powerful compressed tail, point to an animal with the swimming powers of an alligator, but still retaining the ability to travel rapidly on land. Hence *Trachodon* was able to avoid the onslaught

of the omnipresent carnivore, not alone by its speed ashore, but by taking to the water when hard pressed.

Stegosauria (see Pl. 32). — But all herbivorous dinosaurs were not of this defenseless type. The second race, the Stegosauria, or armored dinosaurs, encased the body in an almost impregnable armor, at first quite similar to that of existing crocodiles, whose hide with its contained plates of bone will turn any but the most powerful or skillfully placed rifle bullet. Later the armor became more and more massive, the bony elements being welded into a broad protective shield or carapace covering the creature's back, while the heavily armored tail was like a huge battle mace. As an animated citadel, these animals must have been practically unassailable, for they survived until the very close of the dinosaurian reign.

The most remarkable feature of *Stegosaurus* (Pl. 32, Fig. 5) is perhaps its extremely diminutive brain, which had an estimated weight of but 2.5 ounces, whereas the total weight of the animal must have exceeded that of the largest of living elephants, the brain of which is over twenty times as great. In comparing the relative intelligence of the two, one has to bear in mind the great preponderance of the cerebrum, the seat of the intellect, over the other part of the elephantine brain, whereas in *Stegosaurus* it constituted scarcely more than a third of the entire brain weight. On the other hand, the nerve canal in the sacrum, that portion of the vertebral column which lies between the hips, is of startling dimensions and shows that this part of the spinal cord from which the nerves went out to the great muscles of the hind limbs and tail was not less than twenty times the mass of the brain. Mentally, *Stegosaurus* was superlatively stupid, depending for defense upon the automatic control of the great muscles after the feeble glimmer of thought had given the initial impulse.

In *Trachodon* the brain is smaller than a man's fist and weighs less than a pound. *Brontosaurus* had a brain but little larger, while the large-headed *Triceratops*, to be described later on, with over 10 tons of flesh, possessed a brain weighing not over 2 pounds. Man has an average of about 2 pounds of brain to 100 pounds of total weight, while the dinosaurs did not have one-fourth of this amount of brain to the ton. Or with other comparisons, the brain of the average dinosaur was in proportion to bulk of body a tenth the size of that of a crocodile.

How much of what we term intelligence could such a creature possess? Probably just enough to have eaten when it was hungry, anything more being superfluous. However, intelligence is one thing, life another, and the spinal cord, with its supply of nerve-substance, doubtless looked after the mere mechanical functions of life, and while even the spinal cord is in many cases quite small, the sacral portion is twenty times the bulk of the puny brain. (Lucas.)

With races, as with individuals, there are periods of youth, of maturity, and of old age, terminated in the one by extinction, in the other by death; and as a man bowed down by the weight of years shows unmistakable signs of senility, so the senescence of the race is as clearly indicated to the practised eye by features which in the one case as in the other point to impending dissolution. Among the more striking of these racial old-age characteristics is a relative increase in size beyond the average, and the growth of excrescences of various sorts on diverse portions of the frame, such as the antlers of the deer. *Stegosaurus* in its immense, ill-proportioned bulk, the huge, erect bony plates along its spine, and the spike-like weapons with which its tail was embellished, shows these characters in the extreme, and, speaking metaphorically, is the embodiment of the death agony of a race.

Ceratopsia (see Pl. 33). — The final group of plant-feeders, the horned dinosaurs, mark the culmination of medieval geologic time, for the brief record of their evolution is confined to the latest Mesozoic rocks. These forms had a huge head — in all other types the reverse is true — upon which were horns, two, three, or five in number, borne upon the nose or above the eyes. The neck was protected by a wide-spreading flange of massive bone, typically with serrate edges and invested in a close-fitting covering of horny substance as implied by deep blood-vessel impressions in its outer surface. In the forms in which the nasal horn was dominant, the crest was imperfect, the animal doubtless charging as a rhinoceros might and impaling its enemy with a sweeping upward thrust of its head; while those whose frontal horns were larger were animals of greater bulk and in them the crest reached its highest efficiency, so that a head-on charge of two rival males was comparable to a joust between panoplied knights, the mighty impact of the lance-like horns being deflected by the shield-like flange. That the ceratopsians did fight, and that most desperately, is shown in the grievous "old dints of deepe woundes" that remain on many a skull, fractured and healed jaws and horns, pierced crania and crests. As these were only the relatively few wounds which penetrated the bone, what battle-scarred old veterans they must have been after their century or more of life!

Unlike man and the higher vertebrates, reptiles and fishes do not have a maximum standard of size which is soon reached and rarely exceeded, but continue to grow throughout life, so that the size of a turtle, a crocodile, or a dinosaur tells something of the duration of its life. If tortoises may attain an age of several hundred years, why should not a dinosaur grow to be much older? (Lucas.)

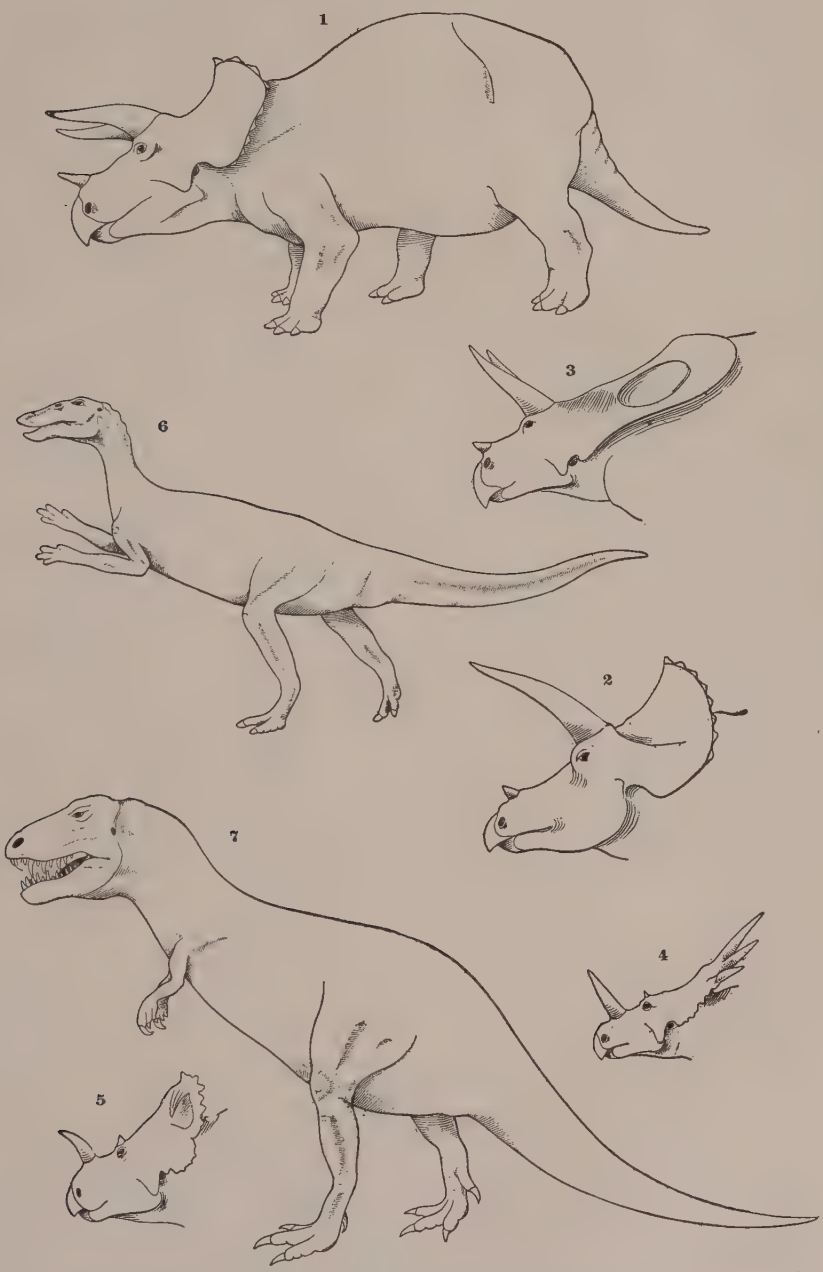


Plate 33. — American Cretaceous dinosaurs (1–5, ceratopsians; 6, predentate; 7, carnivore). Restorations by Lull. See Appendix B.

Did Dinosaurs Lay Eggs? — A point still unsettled is whether the dinosaurs were oviparous or viviparous — did they lay eggs, or were the young born alive? If we are guided by analogy, it might be supposed that, like crocodiles and alligators, these reptiles laid eggs and left them to be hatched by the heat of the sun. As no fossil Mesozoic eggs have as yet been found, the question cannot be answered, though it appears probable that they laid eggs like most other reptiles.

Relation of Dinosaurs to Birds. — The dinosaurs have as many points of structure in common with birds as they do with crocodiles. A very obvious feature of the bird-footed dinosaurs is a three-toed foot; but while this is so very bird-like in appearance, it really is not so important a character as the structure of the shoulder and hip bones and that of the ankle joint, which are extraordinarily like those of a bird. In ourselves and in other mammals, as well as in existing reptiles, the ankle joint is between the bones of the ankle and those of the lower portion of the leg, the tibia and fibula. But in birds and in dinosaurs, some of the ankle bones are united with the leg bones, so that the ankle joint comes in the middle of the ankle itself, and this character is not possessed by other animals, except a few other reptiles.

It is now held that the bird-footed herbivorous dinosaurs (Ornithopoda) and the birds were derived from the same reptilian stock and that in the birds the small, grasping, front limbs have been transformed into wings. This evolution took place earlier than the Upper Jurassic, where undoubted birds — reptilian birds — are known, and it is probable that the beginning goes back to the Triassic. How the evolution went on is not known.

Rise and Succession of Dinosaurs. — As in the history of nations the members of various human races intermingle, so the dinosaurs are interwoven not alone with the various types of their own stock, but with the other kinds of animals and plants which together with physical conditions go to make up the environing complex. A summary of the changing life conditions with their influence on the successive dinosaurian societies is necessary to an understanding of their evolution.

The first relics of dinosaurian life are found in the Middle Triassic rocks of central Europe, though as they appear shortly after those in North America one is led to infer that the initial evolution occurred in Eria. Ancestrally, the dinosaurs were doubtless water-loving quadrupeds remotely related to the crocodiles; but the increasing aridity of climate, clearly indicated by the character of the geologic sediments, placed a high premium on ability to travel rapidly and far in search of food and drink, and may well have been the impelling force that raised these creatures erect from the prone

gait and posture of their progenitors and stimulated their rapid evolution into the several types.

In contrast to marine deposits continental formations are scarce, and yet they alone, with rare exceptions, contain the remains of terrestrial animals. We are given, however, aside from scattered records, three or four vivid pictures of the environment, both physical and organic, wherein the dinosaurs dwelt. Fortunately for us, these glimpses are given in the early stages, in the middle, and at the close of the dinosaurian career, showing the race in the period of its youth, its full maturity, and in its extreme old age.

Late Triassic (see Pl. 31). — The scene of the first of these pictures is laid in what is now the Connecticut valley; the time, late Triassic. Here one must imagine a broad valley rimmed by environing uplands of older rocks, in its climate and sparse vegetation similar to the conditions to be seen to-day by the traveller through the arid regions of the great Southwest. The plant life is sombre: huge scouring rushes, ferns, and pines, with no flowering plants to break the monotony of the dull dust-covered greens. Here and there are dry stream beds carrying at times great floods, while occasionally there are formed extensive bodies of water with characteristic insects, fishes, and crocodile-like reptiles. In the Connecticut valley deposits, skeletons are extremely rare and the few which have been found are largely those of dinosaurs, and in but three or four localities. The footprints, however, for which this region is justly famous, are numberless, and indicate hosts of creatures of more than a hundred kinds, a fuller record of vertebrate life than in any other time and place in the geologic past (Pl. 31, Figs. 1–5). The dinosaurs are mainly carnivorous, though impressions of the feet of herbivores give indubitable evidence of their presence at this time.

During the long Jurassic period, the second division of the Reptilian age, the known fossil-bearing rocks are so largely of marine origin that, except for rare instances where the animal has accidentally been carried into the sea, the record of terrestrial life is almost a blank.

Comanchian (see Pl. 32). — In the Comanchian, however, we have another glimpse of well nigh the entire assemblage of dinosaurian life. The scenes are laid along the eastern United States from Maryland southward, but more notably in Wyoming, Colorado, and Utah, and in the Old World in southern England and northern France and Belgium. In contrast to the aridity of the former scene, the climate is now moist, and the eye ranges over an exten-

sive, low-lying country with misty bayous in which the huge Sauropoda, now in the flower of their evolution, find retreat. The vegetation, though far more luxuriant, is of the same monotonous type as that of the Trias. Here are predentate dinosaurs, armored and unarmored, and while the former are still relatively few, *Stegosaurus* already shows the senile grotesqueness which heralds its extinction. Carnivores, small and large, now in their millennium of numbers and differentiation, ceaselessly seek their prey.

Late Cretaceous (see Pl. 33). — Late Cretaceous time ushers in the third and last scene, of much the same geographic extent as before, but with the sharp contrast of an essentially modernized flora, for the forests now contain many familiar trees and plants, though often in unfamiliar combinations. Again our record is of low-lying country — stretches of everglade and swamp lands with higher areas between — but the denizens have changed; for while the carnivores are now in their maximum of size, the Sauropoda, except for possible survivors in far-off Patagonia, have run their course and died without issue. Unarmored dinosaurs are in their prime, only in rare cases showing indications of degeneracy, while the relatively few heavily armored types are represented by the most impregnable of their race. The horned dinosaurs, apparently exclusively American, begin and end their brief evolutionary career.

Dinosaur Extinction. — One of the most inexplicable of events is the dramatic extinction of this mighty race, for in the rocks of accepted Tertiary age not a single trace of them remains. One student has argued internecine warfare amongst the dinosaurs themselves; another, the destructive slaughter, not of adults but of the young, possibly while yet in the egg, by small bloodthirsty mammals; yet another, change of climate either by the diminution of the necessary heat without which no reptilian race may thrive, or of the moisture with an accompanying change of vegetation. These are all conjectural causes of extinction; but this we know, that with the extensive changes in the elevation of land areas which mark the close of the Mesozoic, came the draining of the great inland Cretaceous seas along the low-lying shores of which the dinosaurs had their home, and with the consequent restriction of old haunts came the blotting out of a heroic race. Their career was not a brief one, for the duration of their recorded evolution was thrice that of the subsequent mammalian age. They do not represent a futile attempt on the part of nature to people the world with creatures of insignificant moment, but are comparable in majestic

rise, slow culmination, and dramatic fall to the greatest nations of antiquity.

Nevertheless their passing was of the utmost importance to a higher race. During the eons of the Mesozoic, from late Triassic time until its close, the mammals, including the remote progenitors of humanity, were in existence, but held in such effective check that their evolutionary progress was practically insignificant. This curb is strikingly illustrated by the wonderful series of tiny jaws and teeth of these diminutive creatures found, in the Comanchian of Wyoming, in actual association with the single tooth of a carnivorous dinosaur, many times the bulk of the largest mammalian jaw.

The removal of this check resulted in the speedy evolution of the archaic mammals into flesh- and plant-feeders, slow-moving and swift. These, because of radical defects of brain and feet and teeth, had but a brief allotted span, and were in their turn displaced by the immigrating hordes of modernized mammals which were to be the rulers of the earth until forced to own the dominance of man.

CHAPTER XLVII

THE JURASSIC PERIOD AND THE MANY KINDS OF REPTILES

In Europe, over the Triassic lies the widely distributed and usually but little disturbed Jurassic, a great series of limestones and shaly limestones attaining to thicknesses of over 3250 feet. The high lands that were made during the close of the Paleozoic had now vanished, and extensive epeiric seas, with a life that was astonishingly rich and varied, gradually spread over Europe. Probably as many kinds of fossils are known from Jurassic rocks alone as from all the other Mesozoic strata combined, and because of this prevalence of organic remains, these formations have been the training grounds for many European stratigraphers and paleontologists.

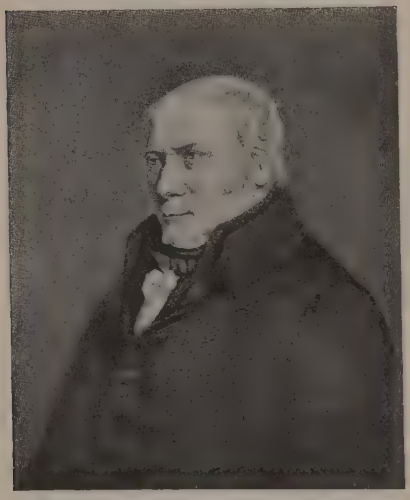


Fig. 463.—William ("Strata") Smith (1769–1839) at the age of sixty-nine. Father of English Geology, and of Stratigraphy.

The Term Jurassic. — In England, these deposits furnished fossils to William Smith, the Father of Stratigraphic Geology (Fig. 463), who was the first to discern in them a value as aids in determining the age of the containing strata. In fact, it is from the Jurassic deposits of England and Germany that the principles upon which Stratigraphic Geology depends have been worked out. At the beginning of the past century, Smith called this system the Oolite series, because so many of its formations abound in oolite structures, so-called from their resemblance to the roe of a fish (see page 275). The earliest division he named Lias, the middle Dogger, and the upper Malm; these are quarrymen's names for local kinds of rock and all of them are still in use, especially in England.

It is interesting to digress here a little, and to note that in the latter country the Jurassic passes through five cycles of sedimentary deposition, that is, the rocks pass five times through the cycle from arenaceous to argillaceous to calcareous strata (Geikie). At one time it was widely held that periods should be based on sedimentary cycles, but the fallacy of this conclusion is seen in that the Jurassic period has within itself five such cycles.

However, as none of the terms used by Smith were based on a definite exposure of rocks, the French geologist, Alexandre Brongniart, in 1829 proposed the name Jurassic for the system, establishing it on the equivalent formations exposed in the Jura Mountains, which lie between France and Switzerland.

Divisions of the European Jurassic. — In Germany, Von Buch in 1839 divided the Jurassic on the basis of rock character into Black (lower), Brown (middle), and White (upper) Jurassic. Later on Quenstedt took up a detailed study of the contained fossils, and in 1858 divided the system into eighteen biologic zones. He was not only a good teacher, but an enthusiastic and genial man, and thus was able to enlist in his work the local collectors of fossils and even the farmers; to this day it is said that the peasants point out his divisions on their farms. Oppel, his student and successor, finally divided the Jurassic into thirty-three zones, many of which are known to have a very wide distribution. More than forty divisions are now recognized, and Buckman predicts that from eighty-five to one hundred biologic divisions (hæmeræ) will be eventually defined. These facts are recited for the dual purpose of showing (1) to what degree of refinement stratigraphy may be developed when an abundance of fossils is present, and (2) that the Jurassic system has so far maintained itself as the best system for exhibiting the principles of zonal correlation.

From the studies of the abundant Jurassic marine faunas came also the first clear ideas of climatic zones in Geology and of world paleogeographic maps, through the work of Professor Neumayr of Vienna. As the result of a long study of the ammonids and their geographic distribution, he came to the conclusion in 1883 that the earth in Jurassic time had clearly marked equatorial, temperate, and cool polar climates, agreeing in the main with the present occurrences of the same zones. The consensus of opinion to-day is that these are representative rather of faunal realms than of temperature belts. On the other hand, it is admitted that there were in the Jurassic clearly marked temperature zones.

North America, however, stands in strong contrast to the European Jurassic development, for the record is one of erosion

and peneplanation over three fourths of the eastern part of this continent. It was only along the Pacific border that the ocean invaded the land and for a limited time extended east as far as Wyoming and Colorado. Probably less than 600 kinds of Jurassic fossils have been described from North America, while Europe has made known nearly 15,000 forms.

Subdivisions of the Jurassic

		Marine Phase of Europe	American Pacific	Cordilleran	American Atlantic
Jurassic	Upper	Portlandian Kimmeridgian Corallian	Colfax, Mariposa } Auriferous	Absent	No stratigraphic record
	Middle	Oxfordian Callovian Bathonian Bajocian	Hinchman Mormon	Sundance Absent	
	Lower	Lias	Hardgrave		

Jurassic Events in Eastern North America

Absence of Jurassic Deposits. — Until recently it was held by many geologists that certain rather local deposits, of continental origin, occurring on the Piedmont Plateau and extending from New Jersey into Virginia, were of Jurassic age. This, the Potomac formation, is now held, on the basis of its entombed plants and dinosaurs, to be of Comanchian time.

Jurassic Erosion Cycle. — In a previous chapter we saw that the Triassic period in eastern North America closed with the Palisade Disturbance, a movement that resulted in the making of block mountains probably as high as the present Sierra Nevadas. Accordingly, Jurassic time opened here with active erosion, and whatever continental deposits were formed at the time were swept into the oceanic basins. Therefore Jurassic time throughout the greater part of North America was one of erosion and without record of the sea or even of the fresh waters. All of the sediments were delivered into the Atlantic beyond the present eastern and southern margins of the continent. This erosion cycle brought about the final transformation from the old topographic expression of high Appalachian and lower Palisade mountains to a nearly base-leveled land, and it was this peneplanation that prepared the way for the next overlap of the Atlantic Ocean, in Comanchian time.

Jurassic of the Cordilleran-Mexican Regions

Northern Pacific Border Area. — In the chapter on the Triassic it was shown that the period closed with crustal warping and deformation all along the entire Pacific border of North America, and that mountain making on a considerable scale took place at least throughout Alaska. In consequence the sea was removed everywhere from the continent, at least from those parts of it now accessible to the geologist. How long this break in sedimentation lasted is not yet known.

The Pacific Ocean again began to invade North America early in Jurassic time, sparingly in the Aleutian Peninsula, the Cook Inlet country of Alaska, and across Vancouver Island. The widest extension at this time occurred in the Californian sea of Oregon, California, and Nevada, where the crustal movements during the Triassic had been only of warping significance (Pl. 34). Of Middle Jurassic events little is as yet well known, other than that the Lower Jurassic of Alaska (1000 to 4000 feet) continues unbroken into the Middle (1500 to 2000 feet) and Upper Jurassic (5000 feet). The total thickness of the marine Jurassic in Alaska exceeds 10,000 feet and consists essentially of coarse deposits, such as tuffs, conglomerates, sandstones, and shales, with lava (andesitic) flows near the top of the series. This is largely the material from the Chitistone mountains formed at the close of the Triassic. The Jurassic series in Alaska along the Pacific border is fossiliferous throughout, though by no means to the extent that is true of Europe. (Stanton and Martin.)

Arctic Alaska. — A very thick series of continental deposits of early Upper Jurassic age has been discovered by Collier in the Cape Lisburne region of Alaska (Pl. 34, Fig. B). The strata, which have been given the name of the Corwin series, consist in the main of coarse deposits, shales with sandstones and some conglomerates, attaining to at least 15,000 feet in thickness, in which there are from forty to fifty low-grade non-coking coal beds, varying in depth from a few inches to 30 feet. Ten beds are each over 4 feet thick, and the total thickness of all the coal seen is 137 feet. The coal is of better grade than lignite. Below these coals are other workable Paleozoic non-coking coals that are of Lower Carboniferous age.

Californian Sea (Walcott, 1894). — The Jurassic marine deposits are widely spread over the states of California, Oregon, and Nevada (Pl. 34). Apparently most or all of Jurassic time is represented, but the detail of the formations is well known only locally, even

though the much-sought-after placer gold of California originally was derived from rocks of this period, the Mariposa and Auriferous slates (Gold Belt series). These Upper Jurassic formations of northern California and the adjacent part of Oregon are essentially sandstones and shales, with very little of limestone and more of tuffaceous conglomerates (500 feet). In places the thickness is 2000 feet, rising to over 6000 feet elsewhere in California, and if the Lower Knoxville strata of 10,000 feet thickness, with their Jurassic flora, belong here, the maximum thickness will rise considerably above the last mentioned figure. In the Humboldt Range of Nevada there are from 1500 to 2000 feet of basal Jurassic (Liassic) limestone, followed above by 4000 feet of slates. Evidently the Upper Jurassic material was derived from a high land, and in places these formations are seen to rest unconformably on the Triassic.

The faunas are always small ones and corals are locally common. During early and middle Jurassic time, the faunal migrations were from the warmer waters of the south, but in the Upper Jurassic (Mariposa, Lower Knoxville) the life was clearly of northern Pacific origin and a part of the boreal or cooler water faunas.

Logan Sea. — Toward the close of the Middle Jurassic, the northern Pacific, with a cool-water fauna, began to spread widely over Alaska and British Columbia and into the states of Montana, Idaho, Wyoming, Colorado, and Utah (Pl. 34, Fig. B). In the Great Plains region the deposits of Logan sea (named after W. N. Logan, who first described its extent) have an average thickness varying between 200 and 400 feet, but increasing to the west to upward of 1000 feet, and in southwestern Wyoming to 3500 feet. The nature of the deposits changes from place to place, and they consist of sandy clays, shaly marls, impure limestones, and sandstones. The cross-bedded sandstones, the changeable sediments, and the universal presence of oysters indicate that the sea was a shallow one, and further, that it flowed over a warped land eroded to a low relief.

Fig. 464. — Characteristic boreal Jurassic bivalve, *Aucella pallasii*.

The fauna is a small, monotonous one, probably not exceeding seventy-five species, and is almost altogether made up of Mollusca, including a few ammonids and squids. The assemblage indicates that the waters did not belong to the open sea, but were those of a large bay and of boreal origin. Among vertebrates, the common forms were the dolphin-like reptiles called ichthyosaurs (page 856), while

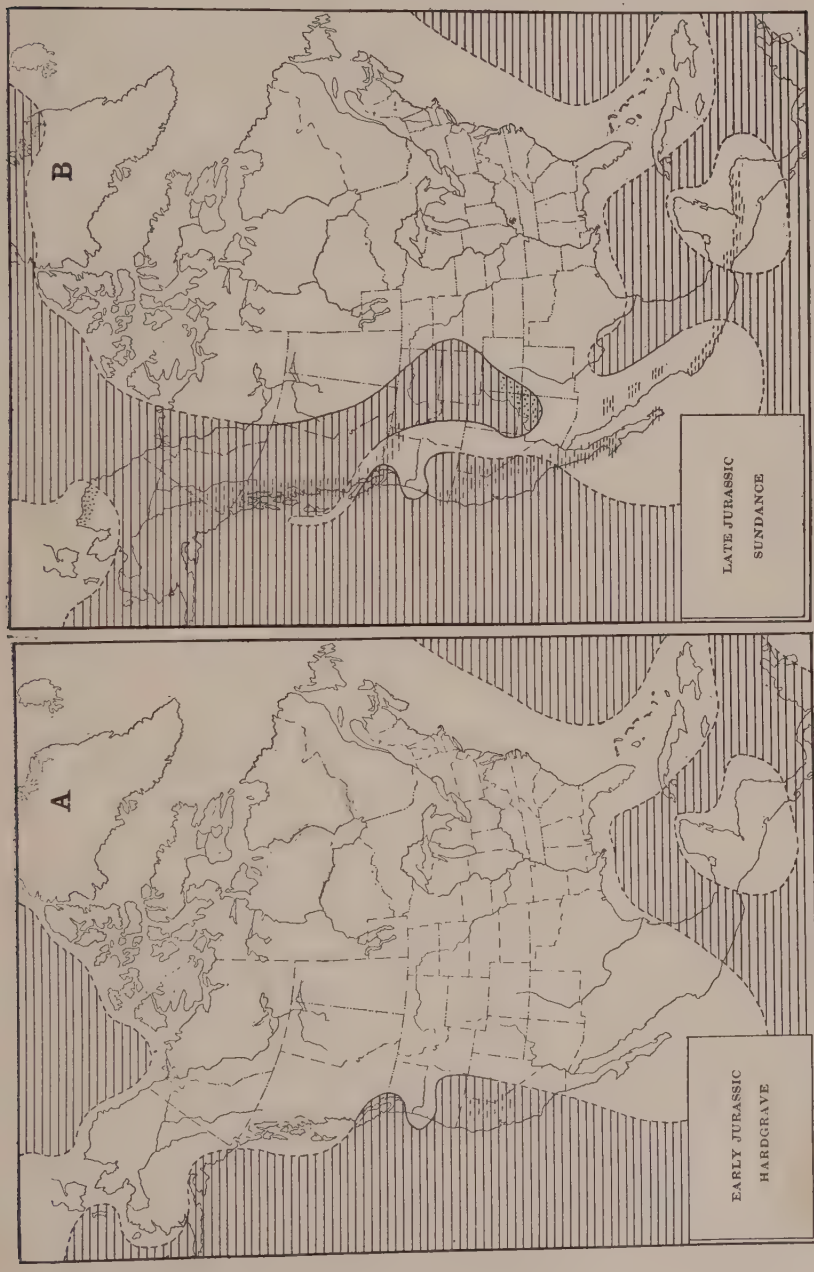


Plate 34. — Jurassic paleogeography. Areas of bathyliths and elevation indicated by dashed lines.

the plesiosaurs (page 857) were rare. The submergence was of short duration and vanished early in the Upper Jurassic before the Alaskan waters began to abound in the boreal bivalves known as *Aucella* (Fig. 464).

Mexico. — Through all of Paleozoic time the greater portion of Mexico was land, and formed a part of the ancient continent Columbia (Fig. 365). Late in the Triassic the Gulf of Mexico spread for the first time over northern Mexico. In the late Middle Jurassic, the greater part of southern and eastern Mexico and southern Texas was flooded by the Gulf and the Pacific, and we shall see further periodic floodings of this land throughout later Mesozoic time (see Pl. 34). The sediments in the main are limestones, with but little of calcareous shales. The thickness of the formations ranges between 1000 and 2000 feet, and they abound in ammonids.

This Mexican subsidence is correlated by Burckhardt with the late Upper Jurassic. The faunas are unlike those of California and have decided European connections, since of the eighty-five ammonids described, eight are identical with those of central Europe and northern Russia, while eleven other forms are closely related. This shows that the western end of Tethys was open into the northern Atlantic and that the faunas migrated along the shores of Gondwana into Mexico.

Volcanic Activity. — In a previous chapter it was stated that volcanoes were active along the Pacific border of North America during Middle and early Upper Triassic time. Similar activity began again locally early in the Jurassic and continued throughout the period, becoming even more marked toward its close than at any time during the Triassic (see Pl. 34). The eruptions were in part submarine, and in part issued from vents situated along the shore line but following in the main the distribution of the Triassic volcanoes. In these lavas basic greenstones, that is, altered basalts, now predominate. (Lindgren.)

Sierra Nevada Disturbance. — At the close of the Jurassic the Sierra Nevadas, the Coast Range of California and the Humboldt Range of Nevada were elevated; also the Cascade and Klamath mountains farther north. These did not then have more than half their present height. The making of the Sierra Nevada Mountains at this time was pointed out by Whitney in 1864 and further described by Dana. Blackwelder (1914) has called this the Nevadian movement, while Smith terms it the Cordilleran Revolution, but the deformation of the crust did not have the extent of a world-wide revolution. Although the mountains mentioned are the regions of most active deformation, it seems probable that movements more or less marked took place from Mexico into southern Alaska. This conclusion is drawn not only from the wide distri-

bution of late Jurassic bathyliths, but also from the fact that at no subsequent time did the Pacific Ocean again spread over the United States so widely as it had previously done.

With the rise of the Sierra Nevadas, there also apparently began the formation of a new trough to the east of the folded area, the *Coloradoan geosyncline*, of which much will be said in discussing the events of the Cretaceous. During Comanchian time, however, this was not decidedly a sinking field.

While the Pacific border of North America was being folded, the earth-shell was also invaded by deep-seated igneous rocks (granodiorite) on a large scale. Magmas in great volume were intruded, forming the great chain of bathyliths now exposed by erosion along the Pacific border from Lower California to the Alaskan Peninsula (see Pl. 34). In comparison with this intrusion, all post-Proterozoic igneous phenomena fade into insignificance. The bathylith of the Sierra Nevada is 400 miles long and has a maximum width of 80 miles, while on the International Boundary there are twelve bathyliths that have a combined width of 350 miles. Farther north appears the Coast Range bathylith, probably the greatest single intrusive mass known, which extends unbroken for 1100 miles into the southern Yukon country, with a width of from 30 to 120 miles. It is thought that while these intrusions began in Middle Jurassic time, the main injections took place at the close of the period, extending into Comanchian time, and that less significant upwellings went on even to the close of the Mesozoic era. (Lindgren, and LeRoy.)

The gold-bearing veins of quartz in the rocks of the Sierra Nevadas have formed as a consequence of the upturning. The wrenching of the strata opened the leaves of the slates and also made great intersecting fissures. The opened spaces and fissures became filled with silica (quartz) deposited by the heated solutions coming from the bathyliths below, which also brought with them the ores now found in the veins. Some of these auriferous quartz veins have a width of 10 to 40 feet. Their erosion has furnished the gold found in the placers (see page 399).

Climate of Jurassic Time

Earliest Jurassic or Lias. — We have seen that in Triassic time volcanoes and lava flows occurred in many places, and that at the close of the period there was considerable mountain making along the northern Pacific border of North America. These movements do not seem to have been of sufficient magnitude to bring on a marked reduction in the climate of the world, and yet a cooled climate is indicated among the animals, as will be shown later.

Students of ammonids say that the closing time of the Triassic was a particularly critical one for this group. Of the more than one thousand known species of Triassic ammonids, not one continued to live into the Jurassic, and the later fullness was developed out of a single family of Triassic time. This extinction and marked evolution along a single line points to marked climatic alterations.

In the Lias there are known 415 species of insects, which remind one much of modern forms. Nearly all were dwarf species, smaller than similar insects living to-day in the same latitude and far smaller than those of the earlier Paleozoic or Upper Jurassic. Handlirsch is positive that this uniform dwarfing of the Liassic insects was due to a reduction of the temperature, and that the climate was then cool and like that of present North Europe. The climate, he states, was certainly cooler than that of the Middle Triassic or of the Upper Jurassic.

With this dwarfing of the insects, and the vanishing of the late Triassic ammonids, there is also to be noted a marked quantitative reduction and geographic restriction among the reef corals of Liassic time. We are therefore seemingly warranted in concluding that the cooling of the climate in latest Triassic and early Jurassic time was not local in character, but was rather of a wide-spread nature.

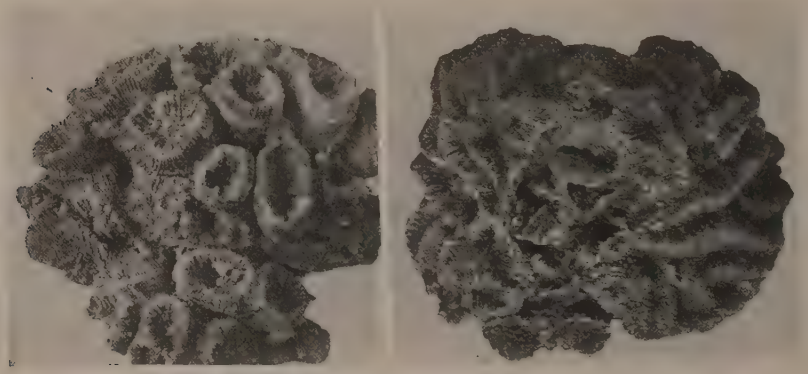


Fig. 465. — Two kinds of Jurassic reef-making Hexacoralla. On right, *Latomœandra seriata;* on left, *Thecosmilia trichotoma.*

Late Jurassic. — The very extensive distribution of Jurassic ammonids shows that there were at that time clearly marked temperature zones, that is, a very wide medial warm-water area, embracing the present equatorial and temperate zones, with cooler but not cold water in the polar areas. That the oceanic waters of

Middle and Upper Jurassic times were warm throughout the greater part of the world is seen not only in the very great abundance of marine life, but also in the far northern distribution of many ammonids, corals (Fig. 465), and marine reptiles. Jurassic rocks often abound in reefs made by sponges, corals, and bryozoans. Jurassic corals occur 2000 miles north of the present occurrence of similar forms. The plant distribution shows clearly that the floras were cosmopolitan and of a moist, warm, and probably subtropical climate. The insects of the Upper Jurassic were again large and abundant, thus confirming the climatic evidence deduced from the plants. In other words, the temperature of late Jurassic time was considerably higher than it had been earlier in the period.

Life of the Jurassic

Land Floras. — The Jurassic floras were truly cosmopolitan, and Knowlton tells us that of the North American species, excluding the cycad trunks (Fig. 318), about half are also found in Japan, Manchuria, Siberia, Arctic Alaska, Spitzbergen, Scandinavia, or England. What is even more remarkable, the Jurassic plants collected by the Shackleton Expedition in Louis Philippe Land, to the south of Cape Horn, in 63° south latitude, are practically the same as those of Yorkshire, England.

The flora of the Jurassic, while in the main a continuation of that of the late Triassic (see Fig. 458), and consisting of rushes or Equisetales, modern herbaceous and tree ferns, cycads, ginkgos, and modern conifers, the descendants of which are now found mainly in southern lands, also shows the incoming of a number of more modern types in these groups. The cycads were of course abundant and diversified, so much so, in fact, that the Jurassic is often called the *Age of Cycads*. In some places, as in the state of Oaxaca, Mexico, the fossil cycads make up 72 per cent of the flora.

Medieval Insects. — While many of the stocks of modern insects are thought to have had their rise in the Triassic, this conclusion is attained only from a study of the Jurassic forms, of which about one thousand species are known, against twenty-seven in the older period. In the Jurassic the insects began to feed on parts of the plants, but probably few as yet visited the inconspicuous flowers of that time for their small amounts of honey. There were as yet no butterflies, but the caddis-flies, the larva of which is known as the caddis-worm, the scorpion-flies, dragon-flies, and beetles were abundant. Other kinds of insects known from this time are the cicadas, grasshoppers, locusts, cockroaches, ants, and termites.

Land Animals. — In general it may be said that the reptiles attained a higher and more diversified development than in the Triassic. True lizards appeared with the Jurassic, and the turtles were then abundant and world-wide in distribution. Although dinosaurs must have abounded in America, none are yet known, since those that were formerly assigned to this period (Morrison) are now regarded by many geologists as of Comanchian age.

One of the most remarkable groups of Jurassic carnivorous reptiles was that of the flying dragons or pterosaurs (from the Greek words meaning *wing-lizard*, see Fig. 466). They appeared late in the Triassic and were characteristic and important in the Jurassic, ranging in size from that of a crow to 3 feet across the wings. The

Fig. 466. — Jurassic "dragon of the air," or pterosaur (*Rhamphorhynchus phyllurus*), × ⅛. After O. C. Marsh.

fore limbs of these animals were modified into wings, as in the bats of to-day, and like them they actually flew. The head was relatively large, but very lightly constructed, and set at right angles with the neck, as in birds.

The joints of the external finger of the hand were much thickened and elongated, this finger being longer than the body and legs together. A membrane devoid of scales and feathers was stretched between the elongated finger on one side and the body and leg on the other, thus forming the wing. The legs, like those of bats, were small and weak, and the tail was very short in some species and very long in others, bearing in one form at least an oar-like expansion at the tip. They were carnivorous animals, feeding in the main on fishes, small reptiles and crustacea. Like most reptiles they probably laid eggs, and may have been warm-blooded.

Birds. — Birds are warm-blooded, very specialized descendants of dinosaur ancestors. They appear as fossils for the first time in the Upper Jurassic and represent one of the most remarkable advances which the life of this period has to show. As yet, only a single kind of Jurassic bird has been found, and this is from the

Fig. 467. — Restoration of the most ancient known bird, *Archæopteryx macrura*, feeding on the fruit of a cycad. After Gerhard Heilmann.

highest division, near Solenhofen, Germany. This bird, about the size of a large pigeon, is called *Archæopteryx* (Greek for *ancient wing*), and has many points of resemblance to the reptiles, and many characters which recur only in the embryos of modern birds (see Figs. 467, 468).

Fig. 468. — Head of *Archæopteryx*, as restored by Heilmann.

The peculiarities which strike one at the first glance are in the head and tail; there was no horny beak, but the jaws were set with a row of small teeth, while the tail was very long and in shape like the leaf of a date palm, composed of separate vertebræ, and with a pair of quill-feathers attached to each joint. The wing was constructed on the same plan as that of a modern bird, but was decidedly more primitive. The four fingers were all free (in recent birds two of the three fingers are fused together); they had the same number of joints as in the lizards and were all provided with claws. The plumage was thoroughly birdlike in character, but was peculiar in the presence of quill-feathers on the legs, and apparently also in the absence of contour feathers from the head, neck, and much of the body, leaving those parts naked. This very extraordinary creature was, then, a true bird, but had retained many features of its reptilian ancestry. (Scott.)

Reptiles of the Seas. — The *Ichthyosauria* (Greek for *fish-lizard*) were a highly characteristic group, for though they appeared in the Triassic and continued into the Comanchian, the Jurassic, and especially the Lower Jurassic, was the time of their principal expansion (Fig. 469). Certain localities in the Lias of England and Germany have furnished an extraordinary number of skeletons, some of the specimens preserving the impressions of the outlines of the body and limbs and showing recognizably the nature of the skin. The ichthyosaurs, Scott tells us, were entirely marine in their habits and preyed upon fishes; their limbs were converted into swimming paddles, and there was a dorsal fin and a large tail-fin, the latter being the principal organ of propulsion. The muzzle was drawn out into an elongated slender snout, armed with numerous sharp teeth, which were set in a continuous groove, instead of in separate sockets. The neck was very short and the skin smooth. In length, these reptiles sometimes exceeded 25 feet, and in appearance they must have been very like the modern porpoises and dolphins. The resemblance, however, is wholly superficial, since porpoises and dolphins are warm-blooded mammals.

Another group of carnivorous marine reptiles was that of the

Plesiosauria (Greek for *near-lizard*), which appeared in the Triassic and culminated in the Jurassic, and which formed a curious contrast to the ichthyosaurs (Fig. 471). In the typical genus, *Plesio-*

Fig. 469. — Restoration of a Jurassic marine fish-lizard (*Ichthyosaurus*). Mother with brood of young. After C. R. Knight and H. F. Osborn. Copyright, American Museum of Natural History.

saurus, the head was relatively very small, and the jaws were provided with large, sharp teeth, set in distinct sockets. The neck was exceedingly long, slender, and serpent-like, and was marked off distinctly from the small, box-like body. The swimming paddles

were much larger than in the ichthyosaurs and probably had more to do with locomotion. The Jurassic species of *Plesiosaurus* did not much exceed a length of 20 feet.

Crocodiles swarmed in the seas and rivers of Jurassic time. In appearance these reptiles resembled the modern gavial of India and had a similar elongate and slender snout. The fore legs were much smaller than the hind, and the animals were probably less exclusively aquatic in their habits than the present-day crocodiles and alligators.

Fishes. — Nearly all of the Paleozoic fishes were absent in the Jurassic, excepting the ganoids and lung-fishes. The former were now at their highest development, not only in the fresh waters, but in the seas as well. Some of these Jurassic forms were evidently the forerunners of modern sturgeons.

The sharks of the seas had attained their modern development, and in the Jurassic the flat fishes known as rays made their appearance.

Marine Invertebrates. — The seas of Jurassic time were replete with invertebrate life. This statement, however, is based on the development of Jurassic rocks in Europe and Asia, where about twenty-five forms are known for each one in America (15,000: 600). As is pointed out elsewhere in this chapter, this dearth of marine

Fig. 470. — Three species of Jurassic bivalves. From left to right, *Trigonia navis*, *T. clavellata*, *T. costata*.

life in America is due mainly to the absence of marine strata and to the fact that when such are present the deposits are not those of normal marine conditions.

The Jurassic rocks abound in microscopic Protozoa of the classes Foraminifera and Radiolaria (described in Chapter L). In the Alps, beds of red flints and jaspery slates (known as radiolarite) are largely made up of radiolarians. Sponges are locally very common and well preserved, and in places make up thick reef limestones. Other reefs are made of modern corals (Hexacoralla) and these are of very wide distribution in the Middle and early Upper Jurassic (see Fig. 465). Crinids are at times common and in the Lower Jurassic are found the largest forms that ever lived, the pentacrinids, which grew to 50 feet in height, with a crown a yard

Fig. 471. — Restoration of Jurassic reptiles known as plesiosaurs, from Germany. In the rear are ichthyosaurs. From Fraas's Guide to the Stuttgart Museum.

in length and width. Since Jurassic times the crinids have played no important rôle in the seas. Sea-urchins of modern types are also common and here appear the so-called irregular urchins (Fig. 393) that later on gave rise to heart-urchins and sand-dollars. The starfishes and brittle-stars are not common, and those present are of modern types.

Brachiopods are still plentiful, but not in great variety, except in the rhynchonellid and terebratulid families. Almost all of the Paleozoic forms vanish with the Jurassic. On the other hand, the rocks of Jurassic time abound in molluscs, which are prophetic of the rise of modern forms. The seas were full of small and large bivalves, some of which were not only very ornate but characteristic of this time (*Trigonia*, Fig. 470, and plicate oysters, Fig. 472). Gastropods are also common and the siphonate forms are the most valuable for historical purposes (see Pl. 37). The most characteristic shell-fish of the Jurassic, however, were the ammonids, to be described in the next chapter. The crustaceans, usually rare as fossils, are represented by many kinds of lobsters in the Upper Jurassic about Solenhofen, Germany, due to unusually favorable conditions of preservation. The ancestors of the modern crabs also appear here (Fig. 474).

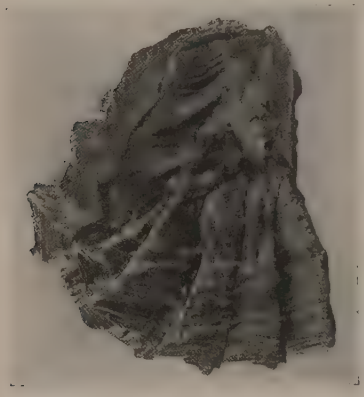


Fig. 472. — Plicated oyster of the Jurassic (*Ostrea marshi*).

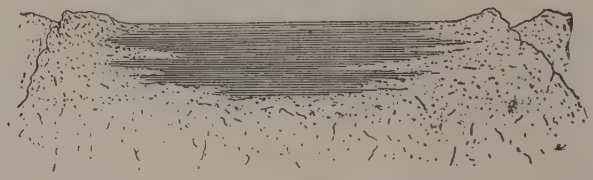


Fig. 473. — Profile through reef-dolomite and lithographic thin-bedded limestone of a Jurassic atoll near Solenhofen, Germany. After J. Walther.

Life of a Jurassic Atoll. — In the region about Solenhofen, during the Upper Jurassic, a series of reefs were built in a more or less circular form by sponges and corals. On the outside of the atolls the deposits are in the main thick series of dolomites and magnesian limestone in heavy beds, while the area inside, never over 75 feet thick, consists of thin-bedded, platy limestone of very fine grain and

of extraordinarily uniform character, representing a limy mud flat, in part permanently under water, and in part flooded twice daily by the tides (Fig. 473). These deposits are the lithographic limestones, which are used throughout the world for the engraving and etching of the monotone and colored prints known as lithographs.

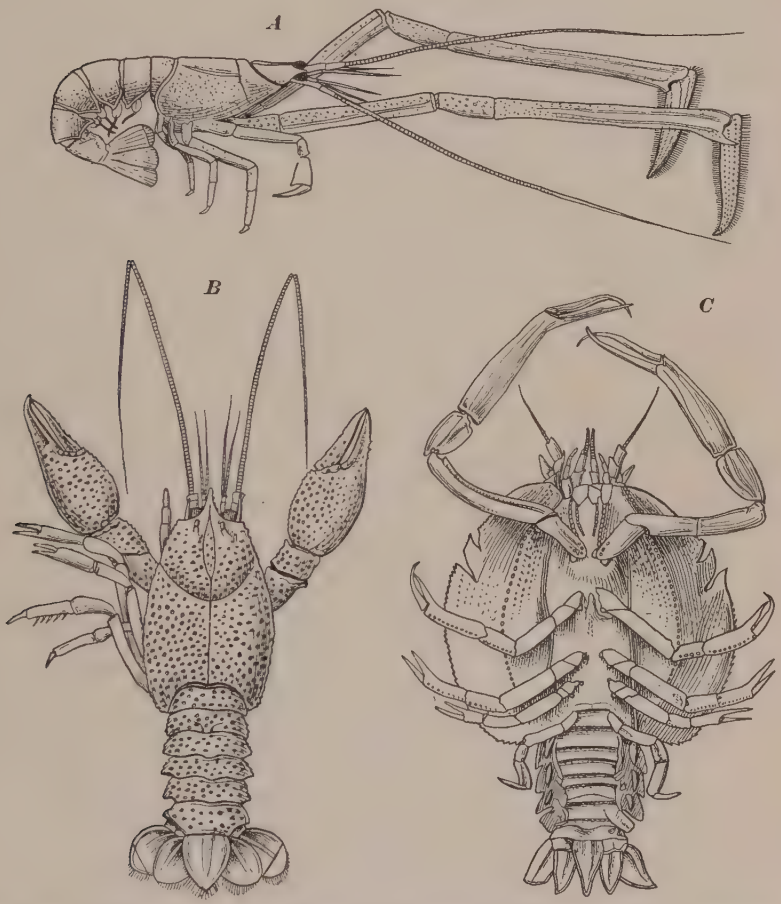


Fig. 474. — Lobsters and crabs from the Jurassic atoll limestones. *A*, *Mecochirus; B*, *Eryma; C*, *Eryon.* After Oppel, from Neumayr's *Erdgeschichte.*

In these platy limestones is found a most wonderful assemblage of animals of the sea and of the land, consisting of forms almost unknown elsewhere. Walther in 1904 monographed this region and its fauna, which amounts to 450 species. The life of the land is represented by a very few plants, more than 100 species of insects, probably blown upon the mud flats from the lands near by, 6 turtles, 9 crocodiles, 1 dinosaur with young, 29 flying reptiles (Pterosauria, Fig. 466), 3 other kinds of reptiles, and the oldest known bird (Fig. 467). Of fresh-water

animals there are none. Of marine fishes, mainly ganoids, there are 143 species, and of crustaceans, mainly of the lobster type (Decapoda, Fig. 474), 71 forms, of ammonids 7, annelids 13, crinids (comatulids) 4, some starfishes, brittle-stars and echinids, and 8 medusæ. All the other types of bottom-living invertebrates, mainly molluscs, are represented by but 40 species that were more or less accidentally drifted into the atoll.

CHAPTER XLVIII

AMMONITES AND BELEMNITES, THE DOMINANT ANIMALS OF MESOZOIC SEAS

Ammonites

General Characters. — The Mesozoic seas were characterized by an abundance of the shelled cephalopods known as ammonids (see Pl. 30). These beautiful coiled shells, relatives of the nautilids, were exceedingly varied in size, shape, ornamentation, and in the character of their septa (the transverse plates dividing the shell cavity into chambers), and more than six thousand forms have been described by paleontologists. Probably the average size would be between 3 and 4 inches, although they may range up to

Fig. 475. — Jurassic ammonite with the animal restored. Rostrum shown in right-hand figure. From Fraas's Guide to the Stuttgart Museum.

diameters of 7 feet, and if the coiled tube in such large ones were straightened out, the length would be between 20 and 35 feet. The ammonids therefore exceeded the Paleozoic nautilids as much in size as they did in specific differentiation. They appear to have been more active animals and better swimmers than the nautilids and therefore crawled less over the bottom of the sea. If they

were good swimmers, they must also have had a functional hyponome (see page 620 and Fig. 379) like the nautilids, but this conclusion is rejected by many paleontologists. The belief that they did swim well is deduced from the nature of the very thin shells, the wide distribution of some of the species, and the small depth, or narrowness, of the coiled cones (see Fig. 475). This statement applies to practically all the tubes that are wound in a plane like a watch spring, but where the shells are spiral, more or less unwound, or straight, they are thicker and the animals are believed to have crawled rather than to have swum (see Pl. 37, Fig. 16). Before proceeding further, the student should refresh his memory by reading what has been said about nautilids on page 619.

History of the Term. — The word *ammonite* goes back to 1732 and the days when fossils were regarded as minerals, as is indicated by the ending *ite*. The shells were so named because of a fancied resemblance to the horns of rams, pictured as one of the attributes of the Egyptian deity Ammon. In India these fossils are current as an article of trade, and they are used throughout that country in certain religious rites.

Comparison with Nautilids. — In many ways the shells of ammonids are like those of the pearly nautilus, but they differ therefrom radically in a number of respects. They are nearly always more ornate, narrower or less deep, and are often distinctly *keeled* along the center of the outer whorls. Further, the mouth of the shells often has lobed extensions on the sides (lappets), and in general there is a median keel that may be drawn out into a sharp point, the rostrum (see Fig. 475). On the other hand, the siphuncle in nautilids is near the center of the septa, but in the ammonids it is always placed near or in contact with the cone on its outer or ventral side (also called venter). In nautilids the mouth of the shell is never closed by an operculum, but in the goniatids and ammonids it probably was closed in most forms by a covering when the animal was at rest. This covering, when thin and made of chitin, is known as the *anaptychus*, but when thick and consisting of carbonate of lime in two hinged pieces is called the *aptychus*.

Nature of Septa. — However, all of these differences, while of importance, are not so valuable in classification as is the nature of the septa (see page 620). In the nautilids these partitions in the chambered shell are simple and more or less concave; in the ammonids, they are simple only in the central part, and each septum becomes more and more fluted or wavy toward its junction with the outer shell (Pl. 30, Figs. 10 and 14). When the outer shell is

absent, as is so often the case in these fossils, the *suture line*, or edge of the septa, is always seen as a wavy line with a distinct pattern, and this pattern also becomes more and more complex with age (see Pl. 30, Fig. 11). It is this complicated suture line, with its intricate *lobes* (inwardly directed) and *saddles* (curved toward the mouth of the shell), that makes these fossils so valuable in deciphering the chronology of Mesozoic time, since it indicates a progressive evolution that has been determined from the sequence of the strata, checked by the individual's growth or ontogeny.

The question is often asked: Why did these animals develop so complicated a type of septum? Among the nautilids we rarely see any approach to the lobed type of septum and here the living chamber is not only variously deep but wide as well. In other words, the ventral side of the cone is rounded and broad, and the shells are usually considerably deeper than those of the ammonids. Therefore the side muscles holding the shell to the animal not only have a greater holding surface in the nautilids, but, what is more important, the cone is more or less round, and therefore rests more uniformly on all parts of the animal, while in the ammonids the shells are lenticular and are therefore more easily turned to one side when in motion through the resisting water. It was probably the narrowness and the appressed nature of the shells that led to lobation of the septa, through the necessity of increasing the holding power of the animal on the shell. In any event, lobed septa are seen only in lenticular shells of cephalopods (nautilids, goniatids, ammonids).

Evolution. — The deep-shelled nautilids late in the Silurian gave rise to small and narrow-shelled *goniatids* with sparingly lobed septa. In most of the goniatids of the Devonian (Pl. 18, Figs. 1–6), the suture line of the lobes and saddles terminates sharply, but in the Mississippian the majority of the species not only have more lobes and saddles, but these are nearly all rounded. Thus we see a gradual change in the narrow-shelled cephalopods, beginning as true nautilids, and passing into various stocks of more or less narrow-shelled goniatids that finally gave rise in the Carboniferous to many lines of evolution among the primitive ammonids, resulting in the establishment of the latter in the warmer Permian waters of the Tethyian mediterranean (Fig. 433). The greatest variation among them took place during late Permian and early Triassic time. At the close of the Triassic they mostly disappeared, probably due to a colder climate and oceanic water. In the Jurassic, there was another rapid evolution out of two or three stocks only and the zenith of development was attained at this time. The waning of the ammonids began in the Comanchian, and during the Cretaceous the stocks showed little of their old virility and far more of old age expression, as seen in the uncoiling of the cones and in

the lack of evolution (see Fig. 495). Their complete extinction came at the close of the Cretaceous during the critical time of the Laramide Revolution.

Belemnites or Ink-fishes

General Description. — In the Mesozoic we likewise see the rise of the belemnites, the ancestors of the cuttle-fishes (also known as cuttles or squids, Fig. 476). The word *belemnite* comes from the Greek name for *dart*, the fossils being regarded at one time as the thunder bolts of Thor, the god of thunder (Fig. 477 *A*). The belemnids were very active, highly carnivorous cephalopods, which fed on fish, crabs and molluscs. They had large and fully developed eyes, were devoid of external shells, and because they had but two internal gill-plumes, the name Dibranchiata has been given to them. They had ten arms, possibly eight short and two long protrusible ones, as in the living squids (Fig. 476). In the Mesozoic these arms were often provided on their inner side with bent chitinous hooks for holding, and, more rarely, with holding suckers. Later the suckers became the dominant type. At first the belemnids had a heavy internal skeleton, but during the Mesozoic, out of the belemnid stock arose the squids, animals that continued as geologic time went on to lose more and more of the ancestral skeleton, though there is still left a vestige of it in all of the living forms.

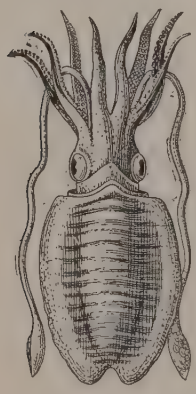


Fig. 476. — Living European ink-fish or sepia (*Sepia officinalis*), as seen from the upper side, much reduced. Note suckers on inner sides of arms. From Woodward's *Life of the Mollusca*.

Ink-sac. — All Dibranchiata are provided with an internal ink-sac containing sepia, a brown-black fluid that mixes readily with the sea-water; this the animals squirt in front of them when in danger and then make their escape backward away from the defensive screen of colored water. The sepia of artists is a pigment made from this substance. Like the other cephalopods, the dibranchiates are provided with a siphon through which water is shot forward, propelling the animal backward. They can also swim by the aid of their side fins.

Nature of Skeleton. — The belemnids originated in the early Triassic (Pl. 30, Fig. 3) out of the Paleozoic orthocerids (Pl. 5, Fig. 17), in that the animals, as it were, made their way more and more out of the external shells and enveloped these by their mantles in

such a manner that they became internal skeletons — an internal pedigree indicating their lineage (see Fig. 477). Among the fossils the part that is usually preserved is called the *guard*, a more or less cigar-shaped, solid, calcareous body, pointed at one end, with a deep circular pit at the other. These guards are sometimes as long as 2 feet and as thick as 4 inches. In the pit of the guards and extending beyond them occurs the chambered and siphunculate *phragmacone*, the vestige of their orthocerid ancestors. This extends forward on the dorsal side into a more or less long piece, either of lime or of chitin, which is known as the *proostracum* (see Fig. 477 *B*). The belemnids are quite characteristic of the Mesozoic, are fine stratigraphic guides, and there are about four hundred kinds known.

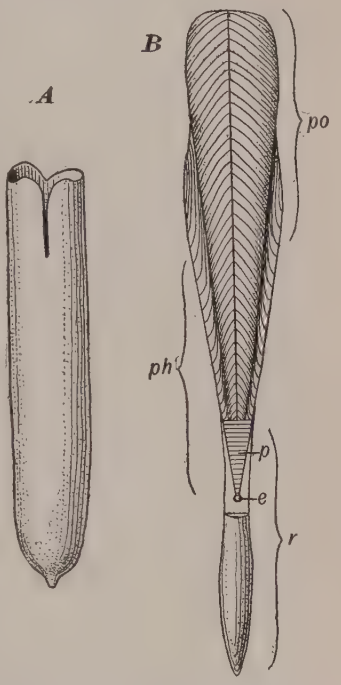


Fig. 477. — Internal skeletons of Mesozoic belemnids. *A*, guard, the commonly preserved part of a Cretaceous form (*Actinocamax quadratus*), about nat. size. *B*, entire skeleton and pen restored. From Steinmann's *Einführung in die Paläontologie*. *e*, embryonic or first shell; *p*, chambered phragmacone (vestige of an orthoceracone) passing upward into the limy or chitinous phragmacone (*ph*); *po*, proostracum; *r*, solid guard or rostrum cut to show chambered phragmacone.

The true squids of the Mesozoic retained only the proostracum and a completely modified remnant of the phragmacone, which together made a thick and wide, but meshy and therefore light, secretion of carbonate of lime, known as the cuttle-bone. Over the proostracum and projecting beyond it toward the head lay the *pen*, so called because it looks like a quill pen, made of chitin. In some of the living squids or cuttles there is left only the pen. In the Upper Jurassic of Solenhofen are found cuttle-bones fully 2 feet long, indicating animals with a probable body length of 6 to 8 feet; in the present seas live the greatest giants, whose bodies are 18 feet long, with the two protrusible arms attaining a length of 30 feet when fully extended.

CHAPTER XLIX

THE COMANCHIAN PERIOD, THE TIME OF GIGANTIC SAUROPODA

History of the Period. — In the early part of the past century the European geologists regarded the rocks overlying the Jurassic as making up the Cretaceous system. At first, this latter system included only deposits of chalk, but gradually more and more formations, of other materials, were added because the fossils clearly linked them together. In this way the Cretaceous came to embrace so great a mass of heterogeneous strata that with the increase of knowledge it became necessary to separate the formations into Lower Cretaceous and Upper Cretaceous divisions. This usage is still generally accepted in Europe, though as long ago as 1887 Neumayr said that if this classification had originated elsewhere than in England, we would then have been regarding the Cretaceous formations as making up two easily separable systems of rocks. In England, the physical characters of the uppermost Lower Cretaceous and the older beds of the Upper Cretaceous are so much alike that no break in sedimentation is readily seen, but on the Continent the separation can everywhere be easily made out. Moreover, the Lower Cretaceous was a rather restricted marine transgression, with widely distributed continental deposits (Wealden), while the sediments of the Upper Cretaceous were almost wholly of marine character and probably record the most marked spreading of the oceans in all geologic time. From these facts we see that the earth underwent two cycles of diastrophism during the " Cretaceous," and the physical evidence is at hand to classify its formations into two systems that in America have recently been called the Comanchian and Cretaceous periods.

It should be stated here that stratigraphers are not yet agreed that Comanchian as defined in this book is a natural system of rocks and represents a period of time that is also recognizable in European rocks and fossils. Comanche series (see below) is clearly a good provincial term and represents a unit of geologic time that is typically developed in the southwestern Gulf States and northern Mexico and from here north to Kansas and Colorado. European geologists say, and perhaps correctly, that the Washita group is Cenomanian in age and hence is not of Lower Cretaceous time, but as it is very closely connected with the rest of the Comanche in Texas, it cannot be separated from the latter.

Plate 35. — Comanchian paleogeography.

Comanche Series of Texas. — Robert T. Hill a number of years ago made a special study of the "Lower Cretaceous" strata in Texas, and in 1887 he proposed for them the name *Comanche series*, because they occur in the home of the Comanche Indians. His ideas gradually prevailed and the rocks and their fossils are now being more and more widely recognized as representing a diastrophic cycle of sedimentation and water movement, the Comanchian period. The succession is best known in central Texas, where there is an abundance of fossils in a thickness of 1500 feet. Hill also divided the system into three series, calling the lower *Trinity*, the middle *Fredericksburg*, and the upper *Washita*.

In central Mexico, where these divisions are not yet clearly made out, the geologists adopt a two-fold separation into Eocretaceous (Lower) and Mesocretaceous (Middle). An older American term, however, is *Shastan*, based on the Shasta group of California and defined by Gabb and Whitney in 1869. This development is wholly distinct, faunally and lithologically, from the Comanche of Texas. They correctly recognized that the group "contains fossils seemingly representing ages from the Gault to the Neocomian, inclusive."

Lower Cretaceous of Europe. — In Europe the Lower Cretaceous appears in two phases: (1) a northern shallow-water, cooler, and more or less brackish one, terminating northward and westward in continental beds (the Wealden); and (2) a southern normal, marine, and warmer water phase that is of wide distribution in the area of the Tethyian mediterranean.

American Phases of Lower Cretaceous. — In America a continental phase occurs to a limited extent along the borders of the Atlantic (Potomac), and extensively in the Rocky Mountains (Morrison and Kootenai). The marine development is of two faunal provinces, (1) a Pacific overlap (Shastan), and (2) a Gulf of Mexico extension widely over Mexico, and in the United States from Texas to Kansas (Comanchian).

The Comanchian deposits may be arranged as follows:

Marine Phase of Europe			American Pacific		Gulf of Mexico		American Atlantic
Gault-Albian			Horse-town	Shastan	Washita	Comanchian	Patapsco
Lower Green-sand	Aptian				Freder-icksburg		Large break
	Barrémian-Urgonian		Knox-ville				Arundel
Hauterivian	Hils or Neocomian	The fresh-water Wealden			Trinity		Break
Valanginian							Patuxent
							Break

Comanchian of Western America

Pacific or Shastan Marine Overlap. — The Sierra Nevada Disturbance at the close of the Jurassic gave birth to a structural valley, now the Great Valley of California, lying between the Coast Range and the Sierra Nevadas. Into this subsiding trough the Shastan sea (Le Conte) spread, while in British Columbia and Alaska the Pacific Ocean gradually encroached more and more widely as a marginal overlap or shelf sea (see Pl. 35). The sediments poured into these seas were coarse-grained and were delivered to them by the rivers flowing out of the highlands to the eastward.

The deposits are essentially sandy shales with thin bands of sandstone, local conglomerates, and rarely thin limestones. The thickness in northern California appears to be between 9000 and 10,000 feet, of which about one third is of Knoxville time, while the remainder is of Horsetown time.

The maximum thickness of the Knoxville in northern California is about 20,000 feet, according to Diller and Stanton. Of this extraordinary thickness, about 16,000 to 17,000 feet is in general poor in fossils but occasionally there are beds replete with *Aucella* (*A. piochii*), a bivalve which is of boreal origin (see Fig. 464). The associated floras, however, Knowlton unhesitatingly refers to the Jurassic. (See page 872.)

The Shastan overlap is also known in northern Washington and along the Canadian and Alaskan coasts. The deposits of these areas are dominantly sandstones with sandy shales, and in most places include considerable thicknesses of volcanic material (from a few hundred feet up to 3350), lavas, tuffs, and ash beds. In the Queen Charlotte Islands, where these strata have coal beds, the depth is estimated at 9500 feet, and elsewhere, although somewhat less, the thicknesses are rarely as low as 2000 feet, but in places the Comanchian strata were entirely removed during the intervals of erosion. Finally, along the Arctic coast of Alaska there also appear to be Comanchian unfossiliferous strata that at Cape Lisburne are over 5000 feet thick.

The Comanchian sands and muds of the Pacific in most places overlap unconformably the older and often metamorphosed formations. This unconformity is often marked, as in the Klamath Mountains and the Coast Range, or is of the erosional type. However, there are also disconformable contacts. The faunas are of the Indo-Pacific realm and are remarkably distinct throughout from those of the Comanchian seas, a condition indicating that the two provinces were completely separated from one another by a land barrier, the western Mexican mass.

The floras of the higher Knoxville (thirty-three species) and of the Horsetown (nineteen) were of the early Comanchian type (Lower Potomac), and flowering plants of the modern types (Angiosperms) are wholly unknown in them. In the Upper Knoxville (4000 feet) the small marine molluscan fauna was still of boreal origin (*Aucella crassicollis* biota). A marked change in the faunas took place in Horsetown time, as the life of the seas then had a Mediterranean (Tethys of India, also of Japan) aspect, a migration that made its appearance earliest in California and Oregon. It, too, was a molluscan fauna of about eighty species, of which over thirty forms were ammonids. This assemblage is known as the Indo-Pacific fauna. (Stanton.)

Fig. 478. — Folded Comanchian limestones in Saltillo Canyon, northern Mexico. Photograph by C. B. Waite.

Mexican or Comanchian Marine Overlap. — From southern Arkansas across central Texas into southeastern Arizona, and thence across almost all of Mexico to the Isthmus of Tehuantepec, are found limestones and marls that are of Comanchian age. These are the deposits of the most extensive inundation by the oceans which befell Mexico and which was greatest here in Middle Comanchian time. Moreover, they form the greatest area of Comanchian rocks and faunas in North America (see Pl. 35). Aguilera of the Mexican Survey states that these deposits make up the main mass of the limestones of the folded mountains of Mexico and in this respect contrast decidedly with the sandy nature of the Shastan sediments. The average thickness is between 3300 (Mazapil) and

4000 (Vera Cruz) feet, and almost all of it is limestone (see Fig. 478). At Bisbee, Arizona, the thickness is about 4700 feet, beginning with conglomerates, thence passing into sandstones, shales and limestones (650 feet), and ending with red shales and variegated sandstones. In northwestern Mexico, about Hermosillo, occurs a very similar succession of strata that are nearly 3000 feet thick and bear coal in the upper beds, according to Dumble. In central Texas, the typical area for Comanchian strata, the thickness is 1500 feet, consisting of limestone, some chalk, but mainly marls and shales, thinning out to a few hundred feet of sands and marls in Arkansas.

Great Plains Extension of the Comanchian Sea. — Late in Comanchian time (Washita) the sea of the Texan area spread northward across New Mexico and Oklahoma, to the south and west of the Quachita Mountains, into central eastern Kansas, southeastern

Fig. 479. — Oyster-like shells of the Comanche of Texas (*Gryphæa mucronata*). After Hill and Vaughan, U. S. Geol. Surv. *A*, upper or free valve. *B* and *C*, lower or attached valves from the inside and outside.

Colorado, and possibly even into central Wyoming (see Pl. 35). This extension did not last long and its deposits consist in the main of muds and marls with sandstones in the west and southwest. The thicknesses are usually less than a few hundred feet, which in the north and east thin down to the vanishing point. The faunas here are always limited but include oyster-like shells (*Gryphæa*, Fig. 479), which often abound in great quantities; evidently the waters were shallow, turbid, and somewhat freshened by the rivers flowing into this extensive bay.

The flora of early Comanchian time (Trinity), as found in Texas, was still Jurassic in character. On the other hand, the plants from the top of the Comanchian (Washita) found in Kansas show that a great change had come over the

forest floras, as flowering plants (Angiosperms) were now present in great numbers and in forms like those of the succeeding Cretaceous.

The marine invertebrate faunas were large and varied, consisting of about four hundred species, and were of normal marine character in Mexico and throughout Texas, becoming less so northward into Kansas and Colorado. The species were essentially of molluscs, with the ammonids making up about one third of the assemblages in Mexico and Texas, though farther north these latter are lacking more and more. Among the bivalves the most characteristic forms were the chamids *Requienia* and *Monopleura*, and the rudistids *Radiolites*, etc. (Fig. 480).

The Comanchian faunas are also widely distributed throughout Central America, and in the high Andes in northwestern and western South America assemblages of these animals are present, though much modified by local evolution. In a general way it may be said that the Comanchian faunas were largely of mediterranean origin (Tethys), or rather that the Gulf of Mexico was in direct connection with the seas of Portugal, Spain, and southern France.

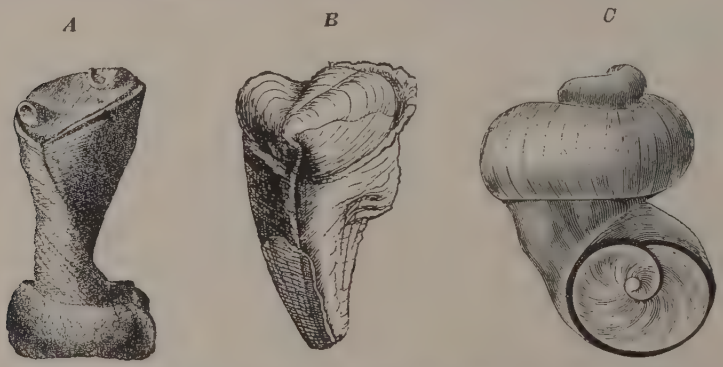


Fig. 480. — Much modified bivalves of the Comanchian. From C. A. White, U. S. Geol. Surv., and Kayser's *Lehrbuch der Geologie*. *A*, entire shell, from Texas, with the right valve attached (*Monopleura marcida*). *B*, a related form from Europe (*M. trilobita*). *C*, a form resembling a snail shell; here it is the large, spirally twisted, left valve that is attached (*Requienia ammonia*).

Morrison Continental Deposits. — Throughout the Great Plains country, from Montana south into New Mexico and overlying the marine Jurassic of the Logan sea, occur variegated green and red marls and shales with irregularly distributed beds of sandstone. They were first studied at Morrison near Denver, Colorado, and at Como Bluff near Medicine Bow, Wyoming. Over large areas the beds at first sight appear to be uniform in character, but seen in detail they vary considerably. The average thickness is about 200 feet, but locally it rises to over 400 feet. Because of the variability in the sediments from place to place, and especially because the strata yield in the main large dinosaurs (see Pl. 32, and Fig. 481), along with some archaic mammals (Fig. 484), fresh-water bivalves,

Fig. 481. — Carnivorous Comanchian (Morrison) dinosaur, *Ceratosaurus*. Length about 20 feet. Note tall tree-ferns in background, and low cycads in foreground, with an archaic mammal hiding among them. After J. Smit, from Knipe's *Nebula to Man*.

snail shells, and land plants, it is apparent that they are of fresh-water origin.

Hatcher held that the Morrison deposits were laid down over a comparatively low and level plain which was occupied by small lakes connected by an interlacing system of river channels. That there were swamps in which the great dinosaurs lived and that they were occasionally entombed therein is attested by the occurrence of more or less complete skeletons preserved in the rocks. Further, there are many fresh-water clams (unionids) and snails. The topography and climatic conditions of that time may be compared to those of the region about the lower reaches of the Amazon to-day.

Ever since 1877, when dinosaurs were recognized as such for the first time, the age of the Morrison has been under discussion. The difficulties in correlation are great because (1) the entombed animals, while abundant, are an isolated occurrence of land animals; and (2) the local stratigraphic position is not clearly defined in the geologic sequence. The strata lie disconformably upon the earliest Upper Jurassic deposits of the Logan sea, and in the same way usually below the Cretaceous (Dakota formation). In recent years, however, Lee and Stanton have shown that the Morrison in Oklahoma and southeastern Colorado actually lies directly beneath the Upper Comanchian (Washita). This then limits its age either to Upper Jurassic or to any Comanchian time older than the upper division or Washita. The only fossils of value in correlation are the dinosaurs, and these agree best with those of the English Wealden, which is now held to be of Lower Comanchian age.

Many years ago Marsh correlated the Morrison with the Wealden, but unfortunately the Europeans have not until recently agreed as to the period age of the latter. Twenty years ago the Wealden was almost always referred to the Upper Jurassic, and this conclusion was followed in America by Marsh and others. During the last decade, however, the tendency has been decidedly in favor of the reference of the Wealden to the older Comanchian, as was definitely proposed by Williston in 1909. Within the past few years giant dinosaurs have also been discovered in German East Africa, and as the containing strata have marine beds of late Jurassic and early Comanchian time associated with them, it is becoming clearer that the Morrison dinosaurs are in all probability likewise of Comanchian age. Moreover, the Morrison dinosaurs have been shown by Lull to agree best with those of the Arundel or middle formation of the Potomac deposits of the Atlantic slope, strata now definitely referred to the Comanchian.

While the Morrison is rich in vertebrate remains, there is little that is distinctively American. The fauna is a derivative of that of Europe, and we may agree with Williston's statement that during Morrison times there was freedom of migration between the eastern and western continents, so free that nothing distinctive of either region was developed through isolation.

Kootenai Continental Deposits. — In southern Alberta (Crowsnest Pass) and in southeastern British Columbia the Comanchian formations are of great thickness along the axis of the Rocky Mountains and are of fresh-water delta origin. These are the Kootenai deposits, chiefly sandstones and sandy shales of very varied texture and appearance, and with many beds of good coal. The maximum thickness of the Kootenai is 5300 feet, with twenty-two workable coal beds, known to extend over an area of nearly 3000 square miles. To the east the Kootenai thins rapidly to 200 feet, with two coal beds. In the Crowsnest area the coals aggregate 216 feet in thickness over an area of 230 square miles. Dowling estimates the coal of this region as equal to nearly 8,000,000,000 tons, and of this about 400,000,000 tons can be classed as anthracite.

The Kootenai is likewise present about Great Falls, Montana, where it is also coal-bearing, though the thickness here does not average over 450 feet, increasing to the west to 1500 feet. Other occurrences are in Wyoming, and in South Dakota (Lakota and Fuson formations), where about a thousand silicified cycad stumps have been found (one of which is illustrated in Fig. 318). The Kootenai in the Great Plains region directly overlies the Morrison.

Kootenai Flora. — The Kootenai fossils are essentially plants, a flora of eighty-six species being known. It is still of Jurassic character, as no flowering plants occur, the forms present consisting mainly of ferns (thirty-four species), cycads (nineteen), and conifers (twenty-five), as seen in Fig. 481. The flora is very similar to that in the Lower Potomac of the Atlantic border, twenty forms being common to the two areas. The botanists are disposed to regard the Kootenai flora as not younger than Middle Comanchian.

Comanchian of Eastern America

Potomac Continental Deposits. — In the chapter on Jurassic events it was stated that the mountains of eastern North America were reduced to a hilly country during that period. It is also true that the main drainage ways, the present large eastward flowing rivers, such as the Potomac, James, etc., were established at the same time. At the very close of the Jurassic it seems that the strand-line of the Atlantic Ocean had been extended further to the west (see page 846), and the continental shelf tilted a little more seaward. Thus the stream grades became more active, and the sediments eroded from the upwarped region were transported eastward to a lower level and spread as the Potomac formation upon the peneplained Piedmont Plateau (the Weverton peneplain) of ancient crystalline rocks. These deposits are now seen all the way from near Philadelphia, past Baltimore and Washington,

through Virginia into Georgia and Alabama (see Pl. 35). There are also scattering exposures in the islands off New England.

The Potomac formation is best developed in Maryland, where the thickness averages between 600 and 700 feet, and all the strata have a slight dip to the southeast, averaging about 40 feet to the mile. The rocks are exposed to the east of the elevated Triassic formations, and further eastward they gradually pass beneath the Cretaceous and Tertiary formations. The deposits consist chiefly of unconsolidated sandy clays, which at the base and in the west have greater amounts of sands and even conglomerates, and then the materials are usually arkosic or replete with fragmented feldspars. In addition, there may be considerable amounts of clay iron-stones (siderite) in the lower part (Arundel formation), and such have been mined in Maryland for more than a century. Because of the presence of these local deposits of iron, the formations assume a red color in weathering, and in the Upper Potomac the deposits are naturally variegated (Patapsco). The Lower Potomac begins with coarse materials highly variable from place to place (Patuxent formation), and finally in the Maryland region a restricted swamp land developed, as seen in the dark and carbonaceous deposits that are even locally lignitic (Arundel). Not only this, but the roots of the forests are still in the place of their origin, and it is in these swamps that the seven species of dinosaurs have been found which link this formation with the Morrison of the Great Plains country.

The Potomac formation is clearly divisible into a lower and an upper series by a marked erosional unconformity. Further, the floras are widely dissimilar in the two parts, since the Lower Potomac still retains the Jurassic aspect, while the Upper Potomac strongly introduces the Cretaceous assemblage of flowering plants or Angiosperms. The Lower Potomac is wholly of fresh-water origin, and was laid down in river valleys over the undulating Weverton peneplain, which had a relief of about 300 feet. On the other hand, the Potomac, although wholly devoid of marine fossils, may be of estuarine origin; that is, it may represent the fresh-water or landward part of the various deltas facing the Atlantic Ocean.

Western Greenland. — In central western Greenland occur Middle Comanchian sandstones alternating with dark shales which have locally very thin and poor beds of coal. This, the Kome formation, appears to be of fresh-water origin, and no marine fossil is known in it. The whole series is about 700 feet thick and reposes on a rather hilly floor of ancient (Proterozoic?) crystalline rocks (see Pl. 35). The flora is rich in ferns (forty species), cycads (eleven), and conifers (eighteen). Of flowering plants there are seven species.

Movements toward the Close of the Comanchian

Cordilleran Intermontane Disturbance (see Fig. 482). — Along the Pacific coast from San Luis Obispo County, California, northward far into Oregon (Coast Range Mountains in wider sense), there is evidence of crustal movement during the Comanchian. Anderson states that the Knoxville is everywhere in this area penetrated and disturbed by dikes and masses of serpentine and accompanying peridotites. Moreover, in the Coast Range of southern

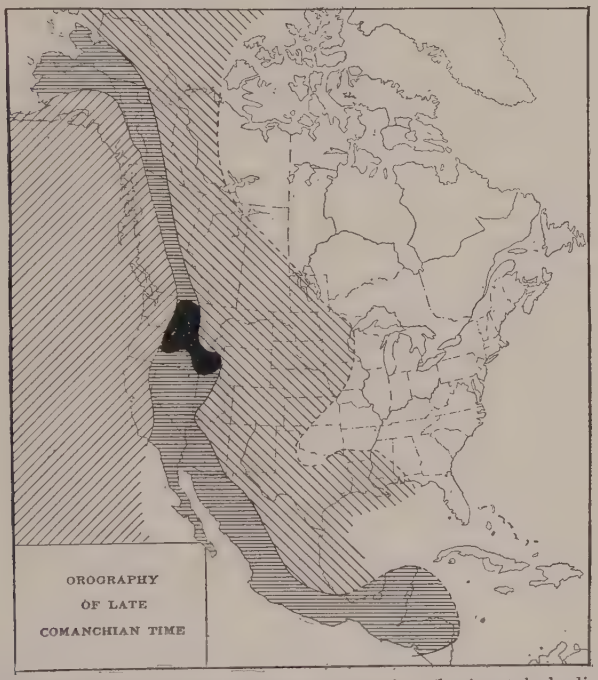


Fig. 482. — Outline map to show regions of elevation (horizontal shading and solid black), the formation of the Coloradoan geosyncline (right-hand diagonal lines), and the Pacific overlap. Generalized from Ransome, *Problems of American Geology*. The black area is that of the present Columbia River Plateau, the region of elevation to the north is known as the Northern Interior Plateaus, while that to the south is the Nevadan-Sonoran Region.

California, where these intruded rocks occur, the Horsetown strata are also absent, while the Cretaceous (Chico) unconformably overlies the older formations.

We have seen in previous chapters that the Pacific transgressed widely over the North American continent during the Triassic and again in the Jurassic, and that these overlaps occurred mainly in the northern or Canadian half of the continent. In the area of the

United States, however, uplift was making itself felt as early as Middle Triassic time, apparently bowing up a low arch in western Utah, eastern Nevada and throughout Idaho, forming together the Columbia River Plateau (black area of Fig. 482), and this arch persisted into late Jurassic time. At the close of the Jurassic, however, the Sierra Nevada folds were thrown up to the southwest of this uplift, and it was then incorporated into the area of the Sierra Nevada Disturbance. This late Jurassic movement also forever shut out the former wide extension of the Pacific, not only from the area of the United States, but from most of western North America as well.

If we next study the paleogeography of Cretaceous time it soon becomes apparent that the conditions of oceanic spreading had been further altered toward the close of the Comanchian, for subsequent to this period the Pacific shelf seas were narrow, and over what is now the site of the Rocky Mountains and far to the east in both Canada and the United States, a new inland sea appeared, the Coloradoan sea of Cretaceous time, extending from the Gulf of Mexico into the Arctic Ocean (Fig. 482). The barrier that kept these waters apart was the newly bowed-up land to the west of the present main Rocky Mountain ridges, the Cordilleran Intermontane Belt of Ransome, and this barrier continued to rise throughout all of Cretaceous time. We see here therefore the beginning of the process which made the Cordilleran Intermontane Belt of elevated plateaus extending from Arctic Alaska all the way into Central America, and it is for this reason that the movement may be called the *Cordilleran Intermontane Disturbance.**

This disturbance also manifested itself in Mexico, for in late Comanchian time western Mexico and Central America into Nicaragua were elevated, shutting out here more or less of the earlier Gulf of Mexico overlap. When the seas of Cretaceous time returned, the life of the former Comanchian was completely changed, very few species being common to the two periods. In this we have the evidence of another break in the record, and one of considerable import for the separation of the Comanchian from the Cretaceous.

Disruption of Gondwana (see Fig. 434). — The great equatorial land across the Atlantic, which had so long united northern Africa to Brazil, was being disrupted by epeirogenic movements during Comanchian time and disappeared beneath the sea during the Cretaceous. The evidence for this is at hand toward the close of the former

* After the above was written a paper by Blackwelder appeared (1914), in which he called this movement the Oregonian Disturbance, but that term is not used here because of its too local significance.

period (Gault time), when the Atlantic began to encroach upon Brazil and equatorial West Africa at Angola. Further and more extensive overlaps were of Eocene time. We may therefore say that the present configuration of the Atlantic Ocean had its origin in late Comanchian time.

Potomac Disturbance. — At Washington the peneplain upon which the Potomac formations repose has a present slope of 112 feet per mile. The subsequent marine plain cut by the Cretaceous seas has a present grade of 33 feet per mile. Therefore these two successive planes are inclined to each other at an angle of 79 feet per mile, and indicate a raising, without folding, of the western Piedmont and Appalachian areas at least several hundred feet. (Barrell.)

Comanchian Climate

Floral Evidence. — On the basis of the floras, Berry holds that the Comanchian climate was considerably warmer than that of to-day, with much less change from season to season, and with a very long growing period. The rainfall was ample and fairly well distributed throughout the year. On the other hand, early in Comanchian time, the climate in polar lands was much cooler, for in King Charles Land (78° N.) Nathorst records trees more than 3 feet thick, having 210 annular rings, indicating that the difference between the seasons was pronounced.

Evidence of Land Animals. — In the temperate and tropical belts, the world in Comanchian time had the greatest of all land animals, the sauropod dinosaurs, reptiles attaining in the United States of America and in equatorial German East Africa a length of about 80 feet (see Pl. 32 and Fig. 481). These animals are thought to have lived in a warm climate in marshes covered with succulent plants along the margins of the continents and in the estuaries of the greater rivers.

Marine Evidence. — The marine faunas were not of warm waters in the far north, for no coral reefs are known there, but their distribution was then in higher latitudes than it is now. In general we may say, therefore, that after early Comanchian time the climate the world over was milder than it is at present and that it was warm temperate in character.

Life of the Comanchian

Floras. — The floras of Comanchian time are everywhere divisible into an early and late phase of development. The older ones, Berry tells us, are those of the Jurassic retained into Coman-

chian time, and they consist of ferns, cycads, and conifers (see Figs. 458 and 481). The rushes, however, had now dwindled into their present meagre representation, and the older Mesozoic ferns were giving way to the modern ones. Finally, in late Comanchian time, the cycads also began to wane, and their places were taken by the flowering plants or Angiosperms which were increasing in importance, for one third of these floras were of this type. They were the ancestors of the modern floras and prophetic of the rise of the living forests. In fact, at least three of the genera are still living (*Sassafras*, *Populus*, *Celastrophyllum*). Between three and four hundred species of Comanchian plants are known in America, and of these about two thirds are of the older development. Before the close of the Comanchian this early hardwood forest of modern appearance had spread to Alaska, Greenland, and Portugal, where elms, oaks, maples, and magnolias occurred, and later in the earliest Cretaceous times it had spread over the entire world.

Dinosaurs. — The reptiles probably attained the zenith of differentiation in the Comanchian, when the dinosaurs were present, not only in greatest variety but in greatest size as well. The most characteristic ones were the Sauropoda (*Brontosaurus* and *Diplodocus*), described at length in Chapter XLVI. The flesh-eating dinosaurs of the Comanchian were also large and terrible, but neither so large nor so ferocious as those of the next period (Fig. 481).

A most interesting burial of plant-feeding, bipedal, Lower Cretaceous dinosaurs has been found in the coal mines near Bernissart, Belgium. These are known as *Iguanodon* and the genus had long been known from single bones found in the Wealden of Europe. In taking out coal the miners came upon a river channel deposit cutting the coal, and in this, over 1000 feet beneath the surface, were twenty-two complete and seven incomplete animals (Fig. 483).

First Frogs.— It is interesting to note here that the oldest American frogs occur in the Comanchian (Morrison) strata of Wyoming (Marsh). They were very small animals and apparently not of much significance in the animal world of their time.

Archaic Mammals. — The rise of the reptilian mammals was noted in the Triassic chapter, and their fragmentary bones, especially teeth and lower jaws, are met with in the various deposits of the Mesozoic. In England they occur at the close of the Jurassic and in the Wealden, and in America in the Morrison (Fig. 484). Little is as yet known of these animals other than that the American and European species were very much alike, and that they belonged to the most primitive mammals, the Multituberculata. It is probable that the Mesozoic mammals were, in the main, egg layers.

Fig. 483. — View in the Royal Museum at Brussels, Belgium, showing nine mounted skeletons of the herbivorous dinosaur *Iguanodon* (*I. bernissartensis*). From a photograph furnished by Professor Dollo.

Marine Life. — The ammonids were still plentiful, though less so than in the Jurassic, but in the Comanchian they began to show a great loss of vitality, in that but few new stocks arose, while old ones were evolving toward a loss of characters and an unwinding of the shell. For other details see Chapter XLVIII. The belemnids were still abundant and flourishing.

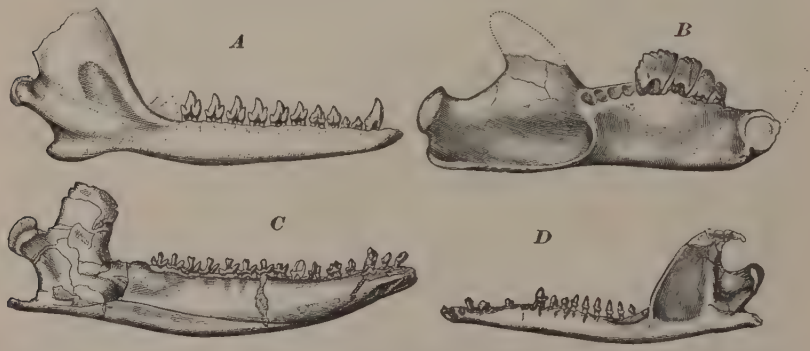


Fig. 484. — Archaic mammal jaws of the Comanchian (Morrison), somewhat enlarged. After O. C. Marsh. *A, Diplocynodon. B, Ctenacodon. C, Dryolestes. D, Stylacodon.*

The other invertebrate life of the sea was not very different from that of the Jurassic, and only a few of the more marked changes need be noted. The sea-urchins were very varied and prolific in the warmer seas, and the heart-urchins (irregular types) here and in the Cretaceous attained their climax of evolution (see Fig. 393). Among the bivalves, the ribbed oysters (Fig. 472) and the oyster-like Gryphæas (Fig. 479) were very abundant, especially in Tethys.

In the boreal seas, the aucellids (Fig. 464) were still plentiful, while in the equatorial waters of Europe, Texas, and Central America there arose remarkably aberrant stocks of bivalves, in which one valve cemented to some object, the shell growing upward into a short or long, twisted, thick cone, while the covering valve was either twisted or a thickened and simple hood (Fig. 480). These were the chamids and rudistids, which also continued into the Cretaceous and there gave rise to the caprinids and larger rudistids, shells that were veritable reef-builders.

CHAPTER L

CHALK AND ITS ORGANISMS

Chalk Deposits. — Although chalk is not the dominant material of the Cretaceous formations, and although it also occurs in the Comanchian, still, because of its conspicuous white color and its fine exposures in the cliffs along both sides of the English Channel (Anglo-Parisian basin), it gave the name to the great system of rocks following the Comanchian, the Cretaceous system (Latin *creta*, chalk).

For a long time chalk was believed to be a deep-sea deposit like the Globigerina oozes (see page 479) of the present abyssal oceans, but the kinds of fossils found in the chalks are indicative of shallow seas, and the formations are often accompanied by sands, while in closely adjacent areas the equivalent strata contain no chalk. In central Wyoming there is much white chalk in the Niobrara formation, but in the western part of that state deposits of the same age are sandy shales or sandstones. In central Kansas the so-called chalk deposits are in reality very fine yellow muds almost devoid of chalk organisms. In western Alabama the Selma chalk is 1000 feet thick, and laterally it changes into marls, clays, and sands. Accordingly it is now held that the chalks are organic accumulations made in the main by the calcareous skeletons of minute pelagic or bottom-living plants and animals, in clear-water epeiric or shelf seas adjacent to low lands with mild climates.

White chalk is a very fine granular limestone, composed in the main of entire or broken calcareous tests of floating or bottom-living Foraminifera (Fig. 485) and of parts of exceedingly small floating calcareous algæ (Rhabdospheres and Coccospheres, described later). With them are often associated many kinds of shallow-water, thick-shelled, bottom-living invertebrates, such as sea-urchins, bryozoans, brachiopods, and molluscs. In Europe the chalks frequently abound also in flints of different shapes and sizes, but in America these secondary alterations are rarely met with. They probably were formed after the chalks had been raised above sea-level, when the atmospheric waters circulating through the porous chalks dissolved the colloidal silica of the sponge spicules

and deposited them as the flints, just as the cherts of limestones are made during the weathering process (see pp. 274 and 437). The flints occur most often along the bedding planes, but are also frequently seen in more or less vertical lines and along the joint planes.

Rhabdospheres and Coccospheres. — The Cretaceous chalk of Europe abounds in the broken parts of microscopic lime-secreting plants, or algæ, known as Coccospheres and Rhabdospheres (Fig. 332). In the present oceans such organisms are characteristic of tropical and subtropical regions, but in the Globigerina oozes their remains are always overshadowed by the greater abundance and larger size of the pelagic foraminifers. Murray states that these pelagic calcareous algæ are so fragile in texture that it is principally their broken-down parts that occur in the oozes, though in places entire specimens of the smallest-sized Coccospheres abound. It is the tiny parts of these calcareous algæ, however, that make up a large portion of the finest materials of the chalks.

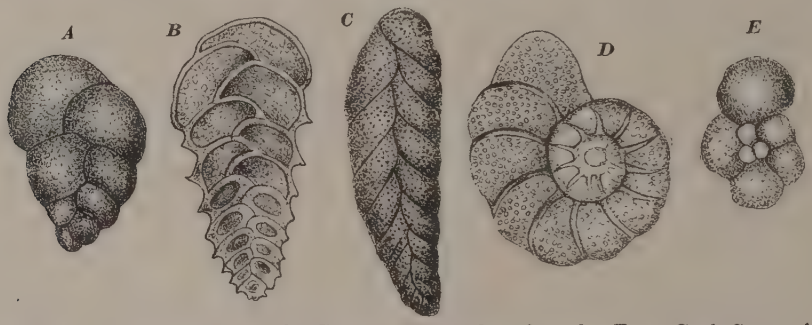


Fig. 485. — Foraminifera of the Cretaceous, greatly enlarged. From Geol. Surv. of Minnesota. *A*, *B*, Two species of *Textularia*. *C*, *Bolivina*. *D*, *Anomalina*. *E*, *Globigerina*.

Foraminifera. — As the chalk deposits are composed in the main of the remains of Foraminifera, it is now necessary to describe these (see Fig. 328, Pl. 20, Figs. 1, 2, Pl. 23, Figs. 1, 2). The name Foraminifera means *having foramina* or holes in the shell, this being the characteristic feature of many of these tiny marine animals, more than two thousand kinds of which are known (Fig. 485). In size the average specimen is smaller than a pin-head, and each individual consists of a single cell of protoplasm, in which all of the functions of life dwell. They constitute one of the divisions in the most primitive stock of animals known as the Protozoa (see pages 415 and 479). The simplest forms (*Amœba*, Fig. 312) are devoid of a shell and the shape of the animal is constantly changing, in that blunt processes are protruded in the direction of movement,

and as they crawl, these pseudopodia, or false feet, as they are called, engulf other organisms on which the Protozoans feed. There is therefore no mouth or stomach, and digestion takes places anywhere within the protoplasm. In the Foraminifera the pseudopodia are more thread-like and issue through the foramina of the shell, or, where these are absent, through a single orifice.

In the protoplasm also lie one or more large, rounded, variable cavities, the *contracting vacuoles* (Fig. 312 *D*, *V*), pulsating organs that have an excretory function and serve to get rid of the finer waste products. Near the center of the cell lies the very important and very complex structure known as the *nucleus* (Fig. 312 *D*, *N*), and here it is that the main vital energy and reproductive processes lie. As a rule, increase in individuals takes place by simple division, beginning first in the nucleus and then going on throughout the cell substance, or the individuals may encyst and develop into many spores, each one of which, when liberated, grows into another individual. In many cases, however, simple division does not continue until complete separation into two individuals takes place (as in Fig. 312 *C*), but the new cells remain united to one another in a definite pattern (as in Fig. 328 *B*, *C*), forming more or less ornate and small or large colonies. In this way thousands upon thousands of individuals may live in a colony, making calcareous structures sometimes as large as 3 inches across.

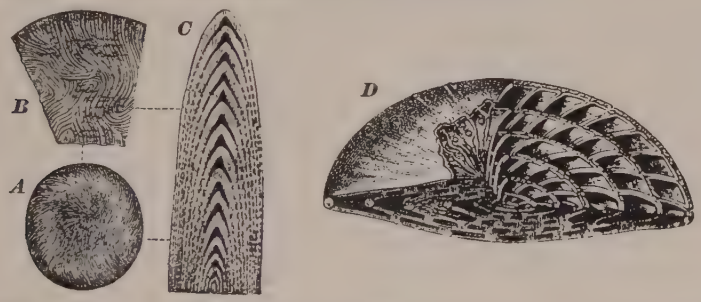


Fig. 486. — Foraminifera (*Nummulina*) in large colonies, from the Eocene of Egypt. From Steinmann's *Einführung in die Paläontologie*. *A*, colony, nat. size. *B*, surface enlarged to show canals. *C* and *D*, portions enlarged to show individual cells or chambers.

Foraminifera are known as fossils since the Cambrian, but did not become geologic factors as makers of limestone until Mississippian time (Pl. 20). In the Pennsylvanian rocks the fusulinid colonies often look like grains of wheat (Pl. 23) and in the early Permian they attained to lengths of an inch. These forms often made limestones and are widely known throughout the northern hemisphere. Throughout the Mesozoic strata, foraminifers are usually present, though commonly in colonial forms of small size, but they are especially abundant after the Middle Jurassic (Fig. 485). The time of dominancy of large colonial forms, however, was during the Eocene in the Tethyian waters. These forms were

the nummulinids (from the Latin *nummus*, a coin), which make coin-shaped colonies usually about three fourths of an inch across, though in cases reaching nearly 8 inches (Fig. 486). They have made a wonderful amount of limestone, especially in the seas now occupied by the Sahara Desert, where the Great Pyramid is built of such stone. After Eocene time, the large colonial forms were no longer abundant and with the warm seas of Oligocene times the modern floating or pelagic kinds took their rise.

Radiolaria. — Another stock of Protozoa related to the Foraminifera are the Radiolaria, so named because of their radiate structure. Their shells are very ornate (see Fig. 330). They are, however, much smaller animals than the foraminifers. Most of them are pelagic in habit, that is, they float in the water of the oceans. Haeckel has published a large volume on the living species gathered by the Challenger Expedition, and in this work he describes 4318 species in 739 genera.

The shells of radiolarians are siliceous and much perforated, and because of their indestructibility the animals are important as rock makers, as is seen from the radiolarian abyssal oozes of the present oceans (see page 480). In the past they have built many fine-grained, siliceous, often red, jasper-like rocks (radiolarites) such as those in the city of San Francisco, California, which are of Miocene age. The oldest Radiolaria occur in the Proterozoic. It should be added here that radiolarian limestones may also be formed in shallow seas, as shown in the Carboniferous of England.

CHAPTER LI

THE CRETACEOUS PERIOD AND THE LARAMIDE REVOLUTION

The Cretaceous system of rocks was the last one formed in the Mesozoic era. The way in which the system received its name from the chalk has been dealt with in the last chapter, and it only remains to be said here that as the lithologic term has been so long in use and is so widely known, the best policy seems to be to continue it.

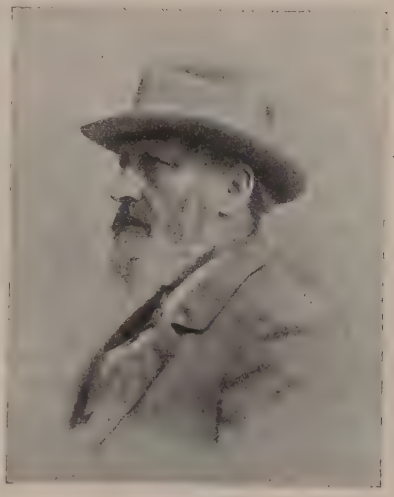


Fig. 487. — Eduard Suess (1831–1914), author of *Das Antlitz der Erde.*

Extensive Cretaceous Submergences. — The Cretaceous was the time when the oceans spread over the peneplained lands apparently more widely than at any other known geologic period. Suess first pointed out this great marine spreading, and it is illustrated in Fig. 488.

The Cretaceous is now divided as follows:

Europe	Great Plains			Texas		Gulf States	Atlantic Coast
Break		Denver, Arapahoe	Shoshone and Lance			Break	Break Manasquan
Danian		Laramie		Break			
Sénonian	Pierre–Fox Hills	Bearpaw, Judith River, Claggett, Eagle	Montana series	Navarro	Gulf series	Ripley	Rancocas Monmouth
				Taylor		Selma	Matawan
Turonian		Niobrara, Benton	Colorado series	Austin, Eagle Ford		Eutaw	Magothy
		(Bear River)				Tuscaloosa	Break Raritan
Cénomanian		Dakota Break		Woodbine Break		Break	Break

Pacific Overlaps on America

Overlying the Comanchian or Shastan strata disconformably, but usually unconformably, is the Chico series of sandstones and shales, with local conglomerates and coal beds. These coarse deposits and thick formations are found all the way from the Lower Yukon, the Alaskan peninsula (1000 feet), Queen Charlotte (11,000 feet) and Vancouver islands (5000 feet), middle and southern Oregon (4000 feet), the Sacramento valley (9500 feet), and the Coast Range of California, to San Diego and the peninsula of Lower California, as far south as 31° 30′. In California there were two periods of volcanic activity and in the Queen Charlotte Islands one of long endurance (see Pl. 36).

These beds begin somewhat earlier in time and continue longer than those of the Colorado series of the great Interior or Coloradoan sea, but do not embrace, according to Stanton, the youngest Cretaceous time.

The Chico faunas were essentially molluscan, and, like those of the earlier Shastan (Horsetown), were of the Indo-Pacific province, and were markedly different from those of the Coloradoan and Mexican seas. A few species of bivalves were common to the two areas mentioned, but these forms were world wide in their distribution. The evidence, then, is decidedly in favor of the view that the Pacific overlap was barred by a land barrier, the rising Rocky Mountains, from entering the Coloradoan epeiric sea.

Great Inland or Epeiric Sea

Coloradoan Sea. — The previous Comanchian submergence finally vanished from all or at least the greater part of the North American continent. After an interval of unknown duration the Gulf of Mexico again began to invade the continent, and more extensively than ever before during the Mesozoic. This was the Cretaceous overlap of vast extent all along the region east of the rising Rocky Mountains from central Mexico into the Arctic Ocean. The invasion began earliest in the Gulf border area, spreading sandstones as a rule in the United States and Canada (Dakota formation) and then muds (Benton) when the sea attained its greatest proportions. In many places, however, the sediments did not begin with sands but with muds. Further, it is probable that the invasion began about the same time in the Arctic region, spreading southward and uniting with the waters of the Gulf of Mexico. This, then, was the great inland Coloradoan sea, and its deposits rest unconformably upon the earlier formations. It takes its name from the older Cretaceous formations, the *Colorado series*, so well developed in the state of that name. This series then continues

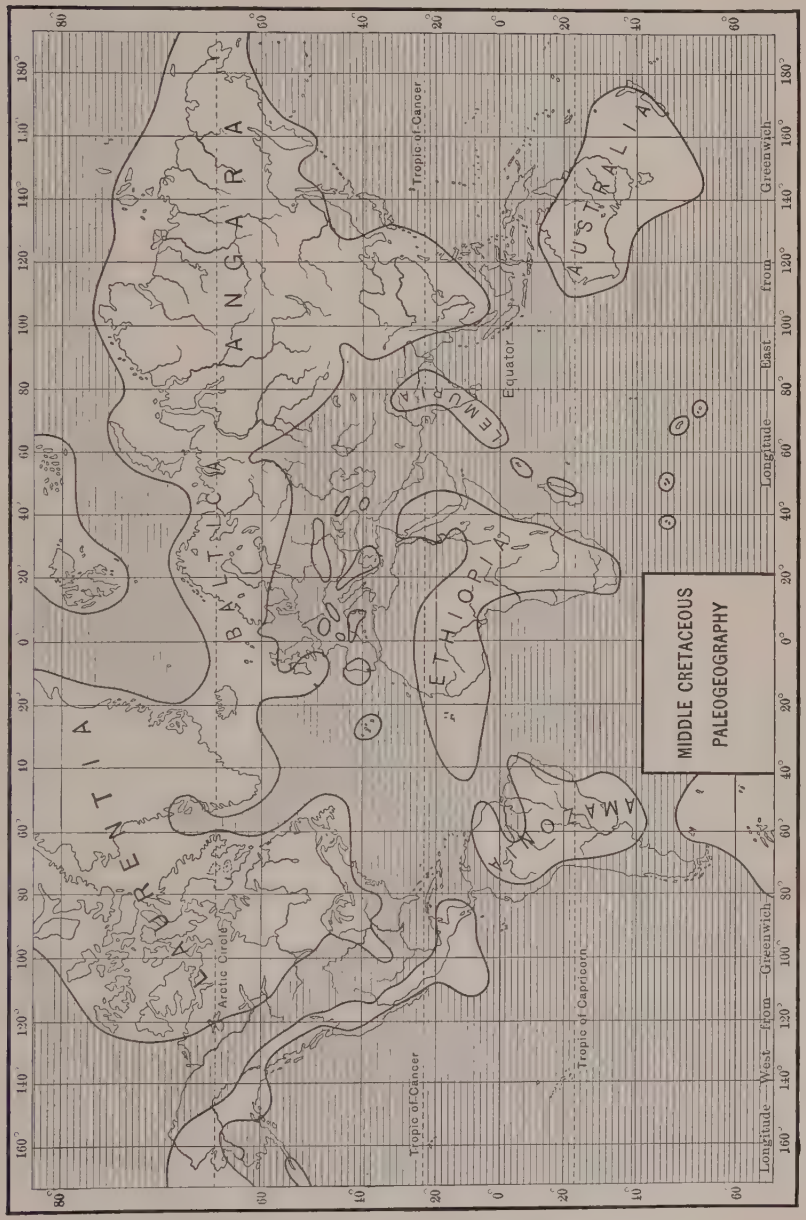


Fig. 488. — The great Middle Cretaceous transgression of the oceans over the lands. In the main after De Lapparent.

unbroken into the upper one, the *Montana series*, of somewhat smaller sea extension (see Pl. 36).

The deposits of the Coloradoan sea are very variable from place to place, and while in the main made up of muds and sands, there are areas of chalk and limestone deposits (Niobrara formation, 200 to 1500 feet thick) in Texas and extending from Kansas and Colorado north into Canada. In general, the formations are thickest in the west, where the materials came from the periodically rising Rocky Mountains, so that brackish and even fresh-water deposits are more frequent here than in the eastern part of the Coloradoan sea. For this reason the greater amount of coal (bituminous and lignite) occurs in the western areas of this seaway. While the coal marshes

Fig 489. — Conformable contact of Cretaceous shales on Devonian limestones (at dotted line near water), 4 miles below Fort McMurray, Athabasca River, Alberta, Canada. Photograph by F. J. Alcock, Geol. Surv. Canada.

were of greatest extent toward the close of the Cretaceous, some coal was laid down in various places throughout this period, evidence which indicates that the sea was shallow, with many deltas in the western area, along with bars and marshy islands, ever changing from place to place, due to the shifting sea currents, the unloading rivers, and the crustal warpings. Finally, the entire Coloradoan basin was silted full, and with the final decided elevation of the Rocky Mountains, this epeiric sea vanished.

In Iowa and Minnesota the Cretaceous deposits are thin, ranging from less than 100 feet to 500 feet, though embracing only the older half of the deposits (Dakota formation and Colorado series). West-

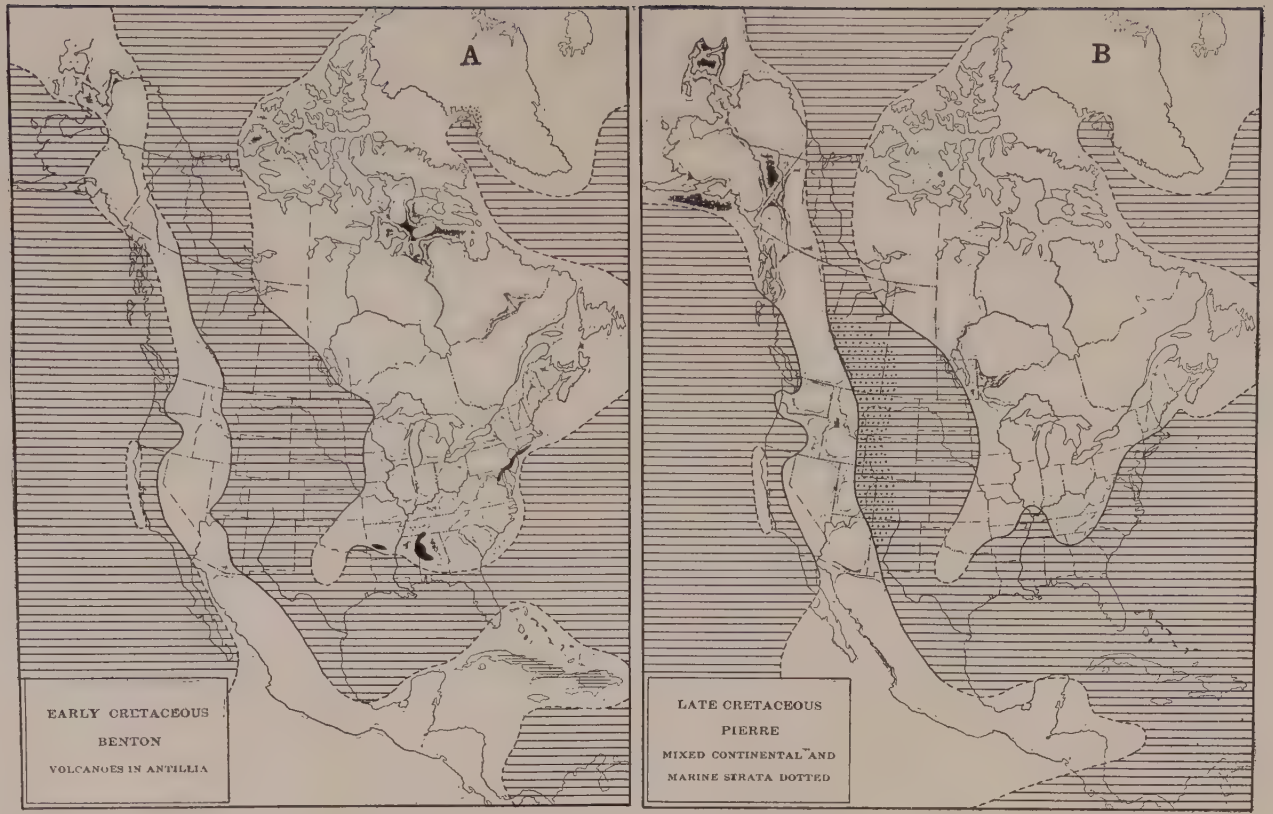


Plate 36. — Cretaceous paleogeography.

ward the formations thicken rapidly, and the rate of deposition increases with time, so that in South Dakota and northwestern Nebraska the depth of the strata is about 4000 feet. In northern central Wyoming and the Great Plains in general, the thickness is about 10,000 feet, and finally in southwestern Wyoming the sections range from 13,000 to over 20,000 feet. These great thicknesses lie in the deepest western part of the basin, and in a general way it can be said that the deposits thin out irregularly both to the north and to the south, though there are notable exceptions to this, as in southwestern Colorado, where the maximum depth is given as less than 7000 feet. In the Big Horn coal basin of Alberta, the thicknesses are also considerable, being about 6200 feet, and this depth is maintained northward into the Saskatchewan country. Still farther north the depths are greatly reduced.

Toward the close of the Cretaceous (Laramie) nearly all of the sea-ways changed from marine to fresh-water conditions, and the sediments were coarse materials (sandstones), often derived from lavas (largely andesites), and ranging in thickness up to 6500 feet. However, at intervals the sea reappeared for a short time throughout the area of the Great Plains, depositing beds a few feet in thickness made up almost entirely of oyster shells. These oscillations of the sea and the general vanishing of the marine waters are prophetic of the coming Laramide Revolution.

Marine Faunas. — The faunas of the Coloradoan sea were made up almost entirely of molluscs, of which the bivalves (*Inoceramus*, with a length of 3.5 feet) and gastropods had the greatest specific development, while the ammonids, now greatly reduced in numbers, are still most significant in determining the geologic age of the strata (see Pl. 37). Corals, sea-urchins and brachiopods, so common in Europe, are almost unknown in deposits of this sea north of Texas. The Coloradoan faunas have their own aspect, with the greatest number of species in common with the Mexican sea and the least with the Atlantic overlap.

Vanishing of the Inland Sea

Final Continental Deposits. — We have seen that the marine Cretaceous of the Rocky Mountains region also has a considerable amount of fresh-water formations, and that the latter tend to recur oftener toward the close of the period. Over them often lie other fresh-water deposits of admitted Tertiary age, and while in places geologists are agreed as to the line of separation between the Cretaceous and Eocene, from the time work was begun in this region of the Great Plains, investigators have often been in doubt as to the division line. In the last ten years this question of classification has become acute, and though many of the best geologists and

Fig. 490. — Restorations of vertebrates of the Cretaceous seas of Kansas. The long-necked reptile attacking the wingless reptilian bird (*Hesperornis*) is a plesiosaur (*Elasmosaurus*); the flying reptiles on the left are dragons or pterosaurs (*Pteranodon*); on the right is a fish-lizard (*Ichthyosaurus*), attacking winged reptilian birds (*Ichthyornis*). After Williston. From University of Chicago Press.

paleontologists have labored toward its solution, the problem is not yet adjusted. The field relations of the formations are fairly well known, but how much value shall be ascribed to the unconformable and disconformable contacts between the series of strata is still an unsettled question. As the sediments come from the same western source as those of the previous formations, they are consequently very much like the older ones. Again, the fossils are not markedly different in their evolutionary change because there is no great lapse of time between the accepted and the debatable Cretaceous formations. There is no lack of fossils in these beds and the difference of opinion among the stratigraphers lies in the fact that the students of invertebrate and vertebrate life find the Cretaceous faunas continued into beds which the paleobotanists hold have floras that are clearly like those of Tertiary time (Fort Union). Or, briefly put, in the same strata the animals appear to be of Cretaceous time while the plants seem to be of the early Tertiary.

The great changes in the animal assemblages of the higher or Tertiary era seen in the rapid vanishing of the old forms and the arrival of unheralded migrants from unknown regions, along with a notable alteration of the climate to somewhat cooler conditions, come later. The age of these younger fossils is not questioned, since they are admitted by all to be of earliest Tertiary time (Fort Union, Puerco, Torrejon formations). In other words, the latest Cretaceous faunas are not transitional in character, while the dinosaurs (of the Lance) continued to live on for a time longer because there was as yet no marked change in their environment. What we have here is a partial record of the interval between the Mesozoic and Tertiary eras, a record that is usually absent at these " critical times." The majority of paleontologists, therefore, prefer to believe that the time is still Cretaceous, though it may later be deemed advisable to say that these persistent faunas continued into earliest Tertiary time. Usually our classifications recognize the beginning of a new history or period by the arrival of strangers, forms prophetic of coming dynasties, and this is what the plants show, but the animals of the lands unfortunately negate this evidence.

Floras of the Final Cretaceous. — As the line of separation between the Mesozoic and Tertiary in the Rocky Mountains is dependent upon the fossil evidence of the strata we must digress a little and present the latter in this place. The latest Cretaceous continental formations (Lance, Denver, Arapahoe) have yielded a flora of 193 species, and of these 84 are specifically identified. It was almost wholly an angiosperm forest flora, of which at least 3 species are still living, a condition unknown in floras of earlier times. Further, it abounded in

poplars (13 species) and planes (8), and of the significantly warm climate trees it had figs (3), magnolias (1), and palms (4). Of this flora about 13 per cent was derived from the Cretaceous, while 81 per cent was Tertiary in character and continued into later times.

Animals of the Final Cretaceous. — Of the described fresh-water shells there are about 39 forms, and of these the unionids were the most prolific (25 species). As these shells were more like those of the earlier Cretaceous, they have little significance as time markers. The rest of the animals, however, were all of Mesozoic types. The mammals were still archaic, and the dinosaurs, of which there is a wonderful record, were absolutely Cretaceous in character, and the last of their race (see Pl. 33). In their evolution they contrast so decidedly with the changing flora that we are compelled to say that the late Cretaceous reptiles were living in a forest of Tertiary aspect. The death knell of the dinosaurs came with the complete vanishing of the Cretaceous epeiric seas and swamps, for none of them are known in accepted earliest Tertiary strata (Fort Union). It may be that their going was further brought about by a somewhat cooled climate, as is seemingly indicated by the Eocene (early Tertiary) glacial deposits or tillites of southwestern Colorado.

Seas of the Final Cretaceous. — In various states of the Great Plains, evidences of late Cretaceous seas are found, the most interesting of which is that of the Cannonball member of the Lance formation of North Dakota, with a known extent of 130 miles. Lloyd divides the Lance into a lower member of continental deposits (400 feet), with dinosaurs, and a flora that Knowlton says is indistinguishable from the plants of the Fort Union (Eocene); and an overlying marine Cannonball member (300 feet), with an invertebrate and vertebrate fauna of over forty species that are very closely related to those of the earlier marine Cretaceous (Fox Hills).

Gulf of Mexico Shelf Seas

Mexican Overlap. — The great inland sea described in the previous pages opened out into the Gulf of Mexico across Texas, where the waters lay upon the margin of the continent and are therefore better referred to as shelf seas. These marginal overlaps came from the Gulf of Mexico and extended all the way from central Mexico across the Gulf States to unite finally with the shelf seas of the Atlantic Ocean.

In southern Texas on the border line of Mexico (Eagle Pass), Cretaceous time is fully represented and there are here about 6550 feet of strata that in the lower portion are made up of clays, marls, chalk and chalky limestones (the Austin chalks and limestones are 1500 feet thick), while the upper 4000 feet consist largely of sandstones and clays, with valuable coal beds, which recur in the state of Coahuila (see Cretaceous-Eocene contact, Fig. 491). The Cretaceous is also well developed throughout northeastern Mexico and as far south as San Luis Potosi in central Mexico, where the Cardenas limestones have an estimated thickness of 1800 feet. South of this

region the formations gradually vanish, and none are known in southern Mexico and the greater part of Central America.

Antillia. — Cretaceous deposits are known in many parts of Cuba, consisting here of magnesian marls and glauconitic limestones. They occur also in San Domingo and Jamaica, where the Blue

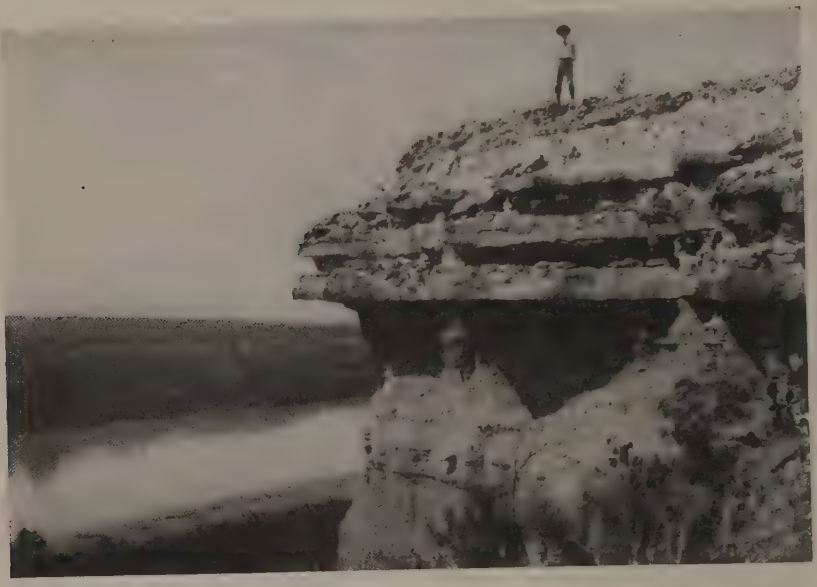


Fig. 491. — Projecting ledges of Eocene (Midway) limestone of the Tertiary resting on Cretaceous shale (Escondido) at White Bluff, Rio Grande, Texas. Note the conformable contact. Photograph by L. W. Stephenson, U. S. Geol. Surv.

Mountain series, 5000 feet thick, begins with tuffs and lavas, passing into dark colored shales, marls and limestones, all resting unconformably upon metamorphosed and igneous formations of older age. These deposits were greatly deformed and injected by igneous material before the opening of Tertiary time, according to Hill.

Life of the Antillian Seas. — The fauna of the Mexican and Antillian seas was of the normal marine type, and of warmer waters. While the molluscs abounded here, the foraminifers, corals, and especially the cemented bivalves (rudistids, Fig. 494) flourished.

Western Gulf Border. — The Gulf of Mexico in Cretaceous times also spread widely over the Gulf States from Texas to Georgia (see Pl. 36). The overlap appeared earliest in Texas in harmony with the early origin of the Coloradoan sea, and did not begin to spread actual marine deposits east of the Mississippi River until the second half of Cretaceous time (Montana). We have seen that

the Cretaceous in southern Texas (Eagle Pass) has a thickness of about 6550 feet, thinning to about 4000 feet in the northeastern part of the state, where the whole of this period is represented by marine beds. Farther east in Arkansas the shore phase of the system is thin, and only the Upper Cretaceous is present, but in Louisiana beneath the Tertiary overlap probably all of the strata are present.

Eastern Gulf Border. — The trough of the Mississippi River is occupied by rocks younger than the Mesozoic, and therefore nothing of these strata is seen except in extreme western Tennessee and southern Illinois. Here on the higher eastern land of the trough,

Fig. 492. — Uneven (erosional) contact of Tertiary marine sands (Midway), with calcareous concretions, on Cretaceous chalk (Selma), at Old Canton Landing, Alabama River, Alabama. Photograph by L. W. Stephenson, U. S. Geol. Surv.

Cretaceous formations that are practically unconsolidated are met with from Tennessee through eastern Mississippi into Alabama and Georgia (see Cretaceous-Eocene contact, Fig. 492). Nearly everywhere they overlap Paleozoic strata, and in Georgia they rest on the more ancient crystallines (Pl. 36). The invasion is variable in time and character of deposits from place to place, beginning as a rule with fresh- to brackish-water sandstones that pass into clays and marls and locally into a thick deposit of impure chalks. The " rotten limestone " or Selma chalk formation of Upper Cretaceous age in western Alabama and eastern Mississippi is 1000 feet thick, but east and west of this area the calcareous deposits are replaced by

marls, clays, and finally sandstones. The thickness of these eastern Cretaceous deposits does not exceed 1300 feet, and usually ranges nearer 500 feet.

Life of the Gulf Seas. — The younger Cretaceous faunas (Montana) of Texas are more harmonious with those of Mexico than with similar horizons of the Coloradoan sea, being probably of waters with a higher temperature. Those of the eastern Gulf border take on more and more of the Atlantic border elements. Almost none of the warmer water rudistids and corals appear east of the Mississippi trough, though foraminifers, sea-urchins, and brachiopods occur here and northeastward, indicating the marine purity of the waters.

Atlantic Shelf Sea

Atlantic Coast. — Upper Cretaceous formations are known all along the Atlantic border, either beneath or inland of the Tertiary marine strata from South Carolina to the south coast of Massachusetts (see Pl. 36). They all dip seaward, though their original position is now warped due to elevating in the west. East of New Jersey the outcrops are scattering and mainly of brackish-water origin, while south of Maryland these deposits are only seen in the river valleys beneath the Tertiary. Therefore the area yielding most information is in New Jersey and Maryland. Here the deposits average between 1000 and 1325 feet, of which the lower 400 to 600 feet are either of fresh-water or brackish-water origin. Here, too, the materials are unconsolidated, and consist in the lower half of gravels, sands, and clays with lignite, while the upper portion is made up of clays and sands becoming more and more glauconitic and finally going over mainly into greensands. Glauconite is characteristic of the Atlantic overlap and at times is also found in considerable quantity in the eastern Gulf border.

Life of the Atlantic Cretaceous. — The marine invertebrate faunas are large, consisting of about 600 forms, in the main Mollusca (Pl. 37). Weller says that many of these have a wide distribution, as many of the New Jersey species also occur in the Gulf border area and mainly east of the Mississippi River. Further, the faunas indicate late Cretaceous time (Montana), and while definite but broad correlations can be made with the formations of the Coloradoan sea, there are not many species in common between the two widely separated areas with which this can be done. The floras occur mainly in the basal formations, where 150 forms have been discovered, and according to Berry their characters indicate a mild climate without marked seasonal changes.

Laramide Revolution

Laramide Volcanoes. — In describing the Cretaceous formations of the Rocky Mountains it was said that more or less of elevation was going on throughout this period, and that toward the close

much lava was ejected and eroded into the andesitic débris seen in the latest marine formations and the subsequent continental deposits. These eruptions continued with unabated vigor into Eocene time, and the volcanoes extended from Mexico City and Arizona north into Canada (see Pl. 36). Volcanoes were also active at this time in Chili, and in peninsular India occurred the *Deccan lava flows* through fissures, the most stupendous eruptions known to geologists, covering an area of 200,000 square miles and ranging in thickness up to a mile or more.

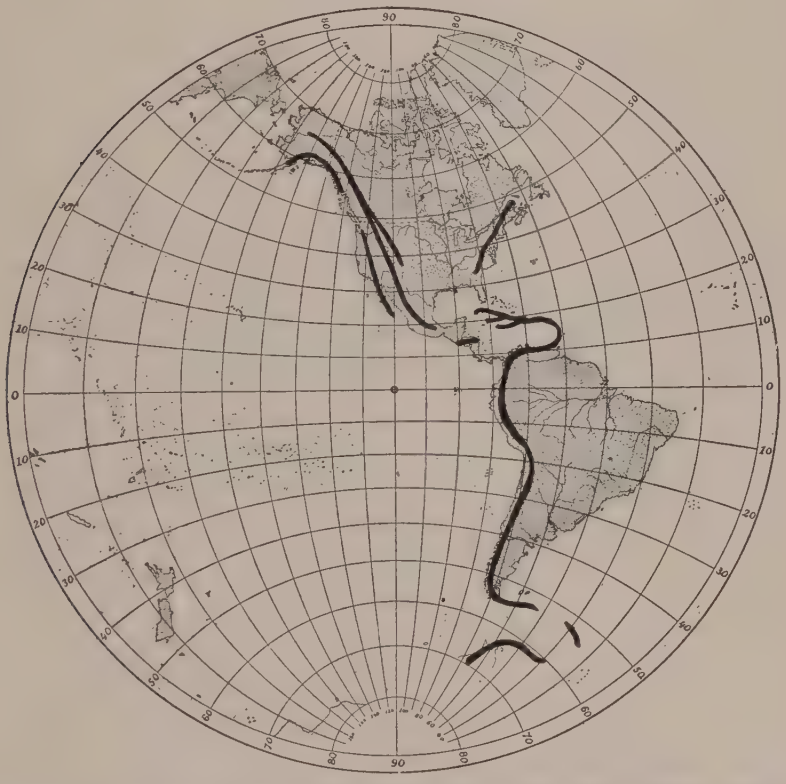


Fig. 493. — Stereographic map of the western hemisphere, after Penfield, showing the Laramide, Antillian, and Andean regions of folded mountains of Cretaceous origin. The Appalachian area was also elevated.

Laramide Mountains. — These volcanic eruptions were but symptoms of crustal movements, for mountain making of a folding nature and due to lateral thrusting toward the east (see page 345) on a vast scale was going on during late Cretaceous time. These movements, though of less intensity, were repeated in the early

Tertiary, and, while the Laramide orogeny was equalled only by that of the closing period of the Paleozoic, it was exceeded by the deformation of late Tertiary time. These movements constitute the Laramide Revolution of Dana. The area affected embraced the mountains of western North America and the Andes of South America as well — two grand mountain chains that extended from Cape Horn to Panama, and from southern Mexico to Alaska — and during the revolution some of the ranges in North America are thought to have had an altitude of 20,000 feet. At the same time the Appalachians were reëlevated, not due to horizontal thrusting but to geanticlinal areal uplift (see page 370), about 2000 feet, and the Antillian mountains were also thrown up higher (see Fig. 493).

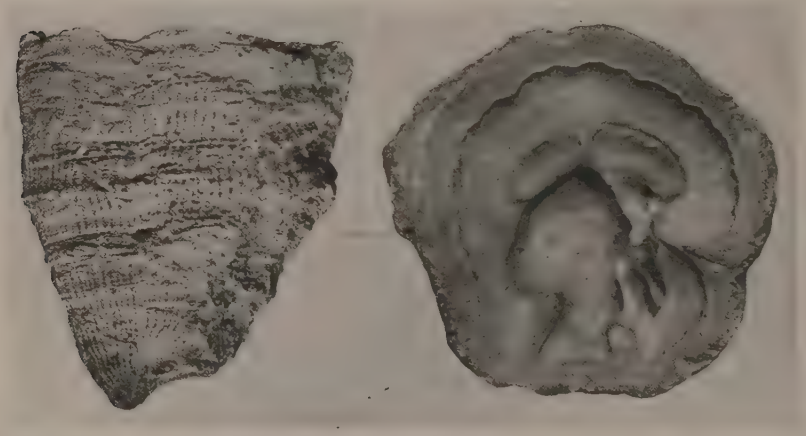


Fig. 494. — Reef-making, coral-like, rudistid bivalves (*Hippurites radiosus*), from the Cretaceous of France. About half nat. size.

Climate of the Cretaceous

The wide distribution of very similar Cretaceous floras, including palms and some fig trees, from Argentina to Greenland and Alaska, indicates, according to Knowlton, a somewhat warmer climate than at present, and one of a moist mild nature in the Rocky Mountains area during the time of the Coloradoan sea.

It is very probable that climatic zones also existed then, though not in so marked a degree as now. This is best seen in the distribution of the marine faunas, for in the Cretaceous formations of Tethys, Antillia, Mexico, and Texas, reef-building corals and bivalves (rudistids, Fig. 494) are conspicuous, while in the deposits

Plate 37. — Cretaceous brachiopods (1, 2) and molluscs (3–16, 3–6 bivalves, 3, 4 oysters, 7–12 gastropods, 13–16 cephalopods or ammonids). See Appendix B.

of North Europe and the American Atlantic border these animals are absent.

We have seen that the Cretaceous closed with the Laramide Revolution, and in harmony with the earlier and later diastrophic movements of similar import, one expects to find here a cold, or at the least a considerably cooled climate the world over, and especially in polar lands. However, no one has yet discovered tillites that were formed during the latest Cretaceous, and even though marked changes took place in the animal world during the Epi-Mesozoic interval and earliest Eocene time, the floras indicate plainly that there was no cold climate accompanying the Laramide Revolution. In the Eocene of Colorado there are local tillites, but these apparently indicate restricted Alpine glaciers and not a world-wide glacial climate.

Two beds of till, presumably from Alpine glaciers, were discovered by Atwood in 1913 in southwestern Colorado, and while their age is not yet determined in detail, Cross holds that they are of early Eocene time. (See page 913.)

Life of the Cretaceous

The life of the Cretaceous was the culmination of the dinosaurs, pterosaurs, and reptilian mammals that began in the Triassic, the toothed birds of Jurassic origin, and the marine faunas of Jurassic time. It was the final expression in the evolution of the medieval life, and out of it arose the modern world of organisms.

Marine Invertebrates. — The invertebrate animals of the Cretaceous seas were much like those of the Comanchian (see Pl. 37), with the marked difference that the ammonids were making their last but ineffectual stand. Old age was upon them and their doom was foreshadowed in the uncoiling, the unnatural twisting of the shells (Pl. 37, Fig. 13), and the straight baculites (Fig. 495, and Pl. 37, Figs. 14, 15). The genus *Heteroceras* displays the extreme of irregular growth (Pl. 37, Fig. 16). The belemnids were still present in force, though by no means so abundant as in the Jurassic, and they were evolving toward the squids in the loss of their internal vestigial structures.

Land and Fresh-water Shells. — The unionids or pearl shells were common, and very much like those now living in the western streams of the United States. Fresh-water snails and land snails (*Helix*, Fig. 376 *C*) are also found, though less commonly.

Floras. — There was nothing medieval in the character of the Cretaceous flora, for more than 90 per cent of the plants were of

the kinds known to-day. The magnolia, fig, and sassafras trees, of Comanchian origin, were in their best development in the Cretaceous. Other modern trees that appeared in this period were the birch, beech, maple, oak, walnut, hazelnut, plane, tulip, laurel, holly, ivy, sweet gum, and bread-fruit. The giant trees of California, the sequoias, of early Mesozoic origin, were also in their

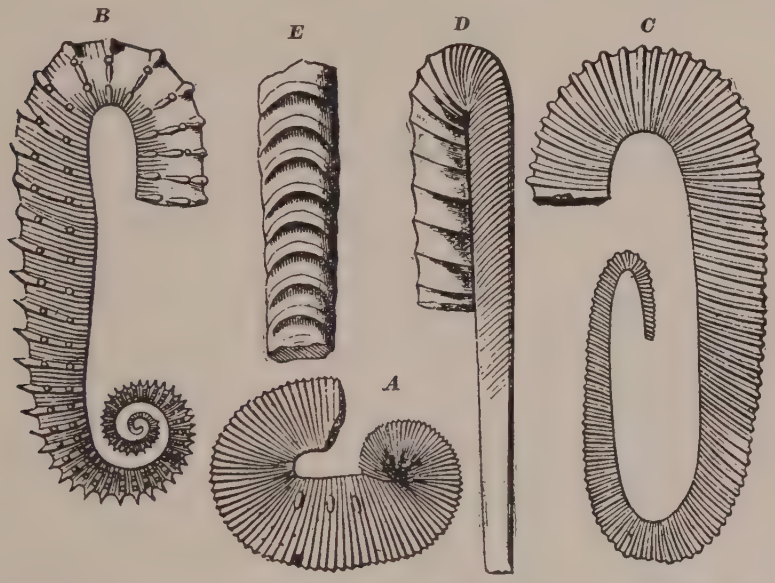


Fig. 495. — Old-age ammonids of the Comanchian and Cretaceous of Europe. From Heer's *Primeval World*. See Appendix B.

ascendancy. The sedges and grasses appeared in Cretaceous time, but it was not until late in the Eocene that the latter and the cereals became abundant, and thus made possible the rise of the higher or placental mammals.

Dinosaurs. — The ponderous, quadrupedal, sauropod dinosaurs of the Comanchian failed to continue their existence into the Cretaceous of North America. With respect to other types of dinosaurs we may say that those of the Cretaceous were more varied and are better known than those of earlier times. The duck-billed, bipedal, plant-feeding dinosaurs were well represented by distinctively American types in New Jersey and especially in the Rocky Mountains (*Trachodon, Claosaurus*, Pl. 33, Fig. 6). On the other hand, the armored dinosaurs that appeared in the Comanchian (*Stegosaurus*, Pl. 32, Fig. 5) are represented in the Cretaceous rocks by different types.

The most common and characteristic of the herbivorous dinosaurs of this time, however, were the Ceratopsia, horned animals, sometimes twice as heavy as and larger than elephants. They are called Ceratopsia (Greek *keras*, a horn) because they have on their heads two or three large horns (Pl. 33, Figs. 1–5). In some ways these animals looked like huge rhinos, but this is merely an external resemblance, for the latter are mammals. However, the Ceratopsia were great fighters among themselves, and against the flesh-feeding dinosaurs their sharp horns must have been formidable weapons. They appear suddenly in the Upper Cretaceous of America, having migrated there from some unknown region.

All of the kinds of dinosaurs mentioned were plant-feeders, and as is the law in nature, they had their carnivorous enemies, the large theropod dinosaurs. Of these there were several kinds, but the most terrible of all in size, weight, and ferocity was the form called by Osborn the King Tyrant Saurian (*Tyrannosaurus rex*), probably the mightiest flesh-feeder of all time, carrying his head 16 feet above the ground and measuring 40 feet along the vertebral column (see Pl. 33, Fig. 7).

At the very close of the Cretaceous, the life of the land was still dominated by the dinosaurs, and nearly all were large compared with the average size of the stocks from which they were derived. Even though the great inland sea along whose shores they lived was vanishing, and the Rocky Mountains were rising, they still lived on without apparent check. It seems probable that some even lived over into Tertiary times, but apparently not long, for the dawn of the Recent was upon them, and the changed environment with its modernizing flora was bringing in a migrant horde of more intelligent and active competitors in the placental mammals. These fundamental changes, accentuated by a cooler climate, brought about their extinction.

Pterosaurs. — Flying reptiles or pterosaurs of early Cretaceous time are known in gigantic species that sailed in swarms over the Kansas seas, their skeletons being common in the deposits of that state (see Fig. 490). They were without teeth and tail, the head was more than 3 feet long, and narrow, while some forms had a long, rudder-like crest extending backward from it 2 feet. They soared over the sea and, diving, like ospreys, picked out of it the fishes on which they fed. Their bones were light and hollow, and their bodies comparatively small when compared with the wing expanse, which in the largest known individual was 25 feet across. These pterosaurs were the organic aëroplanes of Cretaceous time, and

from a study of them Langley obtained hints for his invention of the first flying, or rather soaring, machine of to-day.

Reptiles of the Sea. — The seas of Cretaceous time continued to be dominated by reptiles. The ichthyosaurs were vanishing, but the plesiosaurs attained their culmination, for a form has been found in Kansas which attained a length of 40 to 50 feet, of which 22 feet was neck (*Elasmosaurus*, Fig. 490). The crocodiles were represented by the ancient broad-nosed, long-headed type (*Teleosaurus*), and by the first of the slender-nosed kinds, such as the gavials living to-day in the rivers of India and Borneo. Of marine turtles, at least one kind was present; the largest specimen known was nearly 11 feet long, with a breadth across the front flippers of 12 feet (*Archelon*). But the most interesting of the newly appearing animals were the scaled reptiles known as mosasaurs, which were confined to the Cretaceous. They swarmed in the shallow seas along the Atlantic border and the Gulf of Mexico, and especially in the seas of Kansas. The mosasaurs were gigantic, carnivorous, marine lizards, ranging in length up to 23 feet, with the limbs modified into swimming paddles (see Fig. 496).

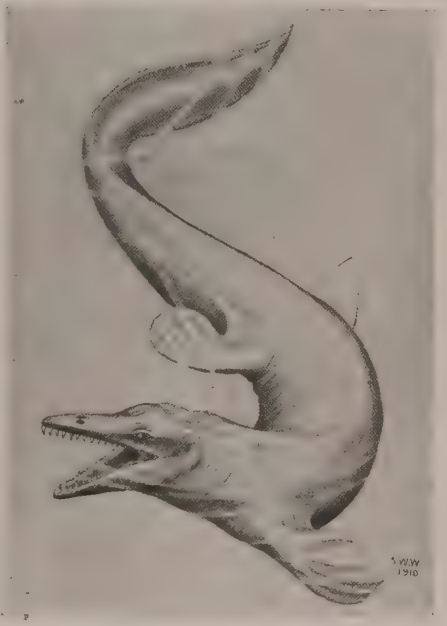


Fig. 496. — A scaled Cretaceous mosasaur (*Clidastes*). From Kansas. Restoration by Williston, from University of Chicago Press.

Birds. — In the early Cretaceous strata of Kansas are found from time to time most excellent skeletons of large reptilian water birds of a species which Marsh called the "regal western bird" (*Hesperornis regalis*, Figs. 490 and 497). The skeleton of this bird measures 6 feet in length, though it did not stand higher than 4 feet; its wings were rudimentary and of no use in air or water, but the great feet were webbed and paddled in the sea with outward lateral instead of downward strokes. Associated with these are found very rarely other much smaller birds with powerful wings

(*Ichthyornis*, Fig. 490). Both of these birds, like those of the Jurassic, had small curved teeth and were flesh feeders.

Mammalia. — Many jaws of diverse kinds of mammals have been found in the very latest Cretaceous deposits (Lance) of

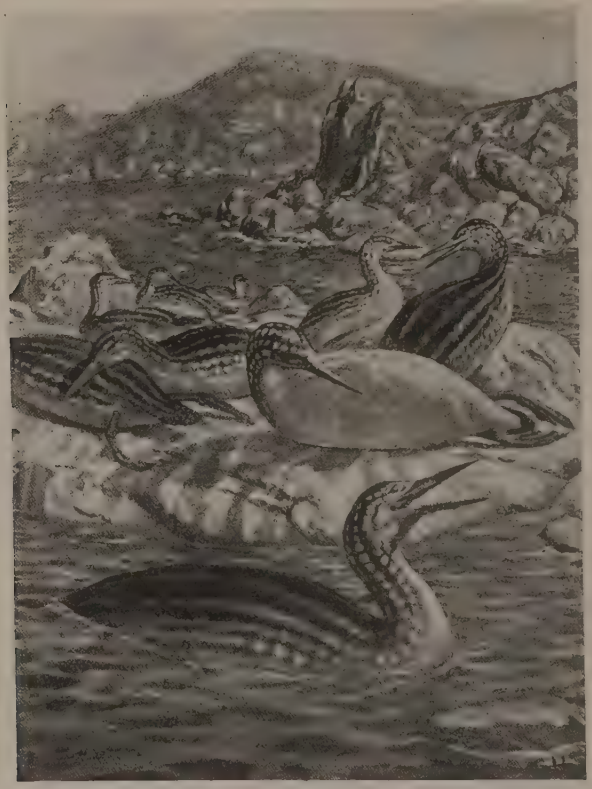


Fig. 497. — Swimming reptilian bird (*Hesperornis regalis*) from the Cretaceous of Kansas. Restoration by Gerhard Heilmann. See also Fig. 490.

Wyoming and Montana, and yet they seem not to have played an important rôle among the land animals of their time; nearly all were still small and of archaic character.

Great Mortality of Cretaceous Time. — We have learned that early in Cretaceous time the oceans began to spread over the continents, and that this transgression was one of the greatest of the geologic past. It therefore is interesting to note that even though there was great opportunity for expansive evolution, but few new marine stocks appeared. On the contrary, it was rather a time of death to many characteristic ones. Entire races of specialized

forms vanished, just as other stocks did at the close of the Paleozoic. In late Cretaceous times it was the ammonids, belemnids, rudistids, and other stocks of molluscs which disappeared. In addition, there was a great reduction among the reef corals, the replacing of the dominant ganoids by the teleosts or bony fishes, and, finally, the complete dying out of the various stocks of marine saurians.

On the land, with the establishing of the highest or flowering plants, we see the vanishing of the dragons or pterodactyls, and, at the very close of the Cretaceous, the last of the dinosaurs and the birds with teeth. In the sea the reptiles were displaced by the teleost fishes; on the land they were overwhelmed by the rise of the mammals; in the air they yielded to the more finely organized birds — in short, the reptilian dominance was destroyed with the end of the Mesozoic era, during which entire time they had been the characteristic animals of the sea and even more of the land.

Economic Products

Coal. — Just as the Pennsylvanian, at the close of the Paleozoic in eastern North America, was the period of greatest coal making, so was the Cretaceous in the Rocky Mountains country at the close of the Mesozoic (see Fig. 438). Some coal was laid down in all of the formations of the Cretaceous, but most of it in the closing time of the period. It is coal formed *in situ*, in local swamps ranging from Arizona into Canada, and occurs in both thin and thick beds (even up to 86 feet), and, as in the Pennsylvanian, usually in many superposed beds. Throughout the Rocky Mountains of the United States there are more than 100,000 square miles of coal-bearing lands, and Colorado alone is estimated to have 34,000,000,000 tons of available coal, most of which is of Cretaceous age. These coals range in grade from lignite to anthracite.

CHAPTER LII

THE DAWN OF THE RECENT IN CENOZOIC TIME

Cenozoic Era

Terminology. — During the rise of the science of Geology, the youngest era in the history of the earth was named *Tertiary* by Cuvier and Brongniart (see page 811), it being thought that all earlier time was comprised in but two other eras. Later came into use the term *Quaternary*, which included the youngest geologic formations of more or less unconsolidated materials scattered over the surface of the earth. This classification arose in western Europe, and was especially based on the sequence in the Paris basin of France. Here the marine formations are interbedded with continental deposits and therefore these two usually independent records, one of the oceans and the other of the lands, are checks upon each other. The shells of the marine formations were studied by Lamarck (1818–1822) and Deshayes (1824–1837), the mammals by Cuvier (1812), and the plants by Brongniart (1822–1828). Deshayes recognized nearly five thousand kinds of shells and the study of these led him to see that the youngest strata had the greatest number of still living species, while the forms found in the oldest rocks had the least faunal resemblance to those of the present. This change or evolution among the shells was taken by Charles Lyell (Fig. 498) in 1832 as the basis for dividing the Tertiary formations into *Pliocene* (from the Greek words meaning *more recent*, 35 to 50 per cent of the species still living), *Miocene* (*less recent*, 17 per cent still living), and *Eocene* (*dawn of the recent*, 3.5 per cent still living). To these Lyell later added *Pleistocene* (*most recent*,

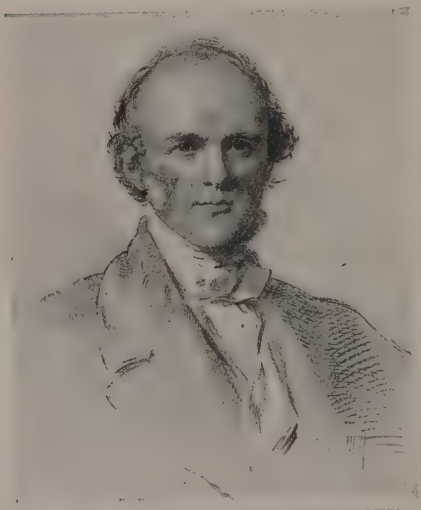


Fig. 498. — Sir Charles Lyell (1797–1875). Author of *Principles of Geology*.

90 to 95 per cent still living); and in 1854 Beyrich separated out the older Miocene formations under the term *Oligocene* (*little of the recent*). Finally Schimper (1874) showed that the very oldest Tertiary strata should be distinguished as *Paleocene* or *old Eocene*. A wider knowledge of the marine Tertiary molluscs has shown that this classification has permanent value, but that the percentage of living species is about as follows (see also page 442):

Quaternary		Pleistocene,	from 90 to 100 per cent of living Mollusca
Tertiary	Neogene	Pliocene,	" 50 to 90 " " " " " "
		Miocene,	" 20 to 40 " " " " " "
	Paleogene	Oligocene,	" 10 to 15 " " " " " "
		Eocene,	" 1 to 5 " " " " " "
		Paleocene,	practically no living Mollusca

Stratigraphic Relations to Mesozoic. — Everywhere the marine Tertiary is easily distinguished from the Mesozoic or older strata because of marked unconformities or disconformities that represent a long break in sedimentation, as is indicated by the marked differences in the faunas of the Cretaceous and Eocene formations. However, in places where Paleocene formations of fresh-water origin repose upon other continental deposits of late Cretaceous age, the separation is often very difficult to make, and this is at present the case in the Rocky Mountains area (see page 894).

Degree of Consolidation of Strata. — Where the Cenozoic strata have not been deformed, they are apt to be unconsolidated and soft, as in the marine formations along the Atlantic border and in the continental deposits of the Rocky Mountains. Along the Pacific coast, however, nearly all of the formations older than the Pleistocene are folded or otherwise altered so that they are as much consolidated as are the formations of the Paleozoic.

Life Characteristics. — The life of the oceans and the continents during Cenozoic time gradually evolved into that of the present day. This is especially true for the land animals but is less so for the land floras, since the latter had already taken on the expression of the Recent during the Cretaceous, as explained on page 904. The grasses became ever more prominent during the Tertiary and took possession of the open plains in the Miocene, leading to a general change in the evolution of the herbivorous mammals. The palms, of Cretaceous origin, became common throughout the world during the first half of Tertiary time, but of the once world-wide sequoias only two species are still living in isolated areas in California. The magnificent dinosaur development and the wonderful flying dragons or pterosaurs of the Mesozoic were gone, and all of the more

characteristic reptiles of the sea (ichthyosaurs, plesiosaurs, mosasaurs, see page 907) were wanting in the Tertiary. With the Eocene came the rise of the modern mammals, the most striking change in the life of the Tertiary, and their wonderful evolution and expansion over the continents will be described in Chapter LIII.

The reptilian toothed birds vanished with the Cretaceous, most of the living families of birds taking their rise in the Eocene. Here there was a more advanced and also a more varied bird life, a conspicuous element in it being large flightless forms resembling ostriches.

In the Eocene and Oligocene, large crocodiles were still common, and a great variety of turtles as well. Snakes and lizards of Mesozoic origin were more abundant in the Tertiary, and at that time arose the venomous snakes.

Among the insects, the most fundamental changes took place in the Permian, but the modern types originated in large part in the earlier half of the Mesozoic, although the butterflies were of Tertiary origin. More than six thousand species of Cenozoic insects are known, and it may be said that the fullness of insect life was attained in the Miocene. About Florissant, Colorado, there was a lake in Miocene time, surrounded by active explosive volcanoes. The ashes from these volcanoes fell into the waters, entombing the flora and countless numbers of insects, chiefly beetles, more than one thousand kinds being known.

The invertebrate life of the Tertiary marine waters was practically the same as that of to-day, though it should be said that it took on more and more of the Recent development during this era. Of the grand array of Mesozoic ammonites, not one species lived over into the Cenozoic, and the same is almost true of the belemnids.

While the corals were of modern types, they appear to have been no more conspicuous than they are now. The bivalves were particularly common and modern, and prominent among them were the many kinds with large siphons, the shell being buried in the mud. Oysters attained their climax of development in the Miocene of California, where the giants had a length of 13 inches, a width of 8 inches, and a depth of 6 inches. Finally, attention should be directed to the crabs, which were common in the Oligocene and Miocene. In the later Eocene occurred the first mammal adaptation to an oceanic life, in the form of whale-like animals (*Zeuglodon*). In the Oligocene came that of the sea-cows, and in the Miocene, that of the true whales, seals, and sea-lions.

Climate. — In early Tertiary time the climate, as shown chiefly by the plants, was marked by belts of temperature slightly cooler than during either the preceding Cretaceous or the succeeding Oligocene, when the temperatures were warm and equable throughout the world. With the Miocene, another reduction of temperature developed, probably due to the rising of the mountains, the foundering of parts of Eria permitting the colder Arctic waters to enter the Atlantic and

thus to cool this ocean. The climate continued to grow cooler to the close of the Pliocene, and in the Pleistocene occurred one of the two most marked glacial climates known to geologists, described in Chapter LIV.

Eocene Tillites of Colorado. — Professor Atwood in 1913 discovered at a number of localities in the San Juan Mountains of Colorado beds of tillite, ranging in thickness from 80 to 100 feet. The material was derived from high mountains fully 40 miles away, which then stood to the south and southeast of the present till areas. The tillites unconformably overlie the Cretaceous and are covered by Eocene tuffs, indicating a probable early Eocene age. It is to be expected that other areas of these tills will be found, in which event it will appear that the Laramide mountains were then widely covered by alpine and piedmont glaciers.

Areas of Sedimentation

The seas of Cenozoic time in North America were typically marginal overlaps of the oceans, and were of the nature of epicontinental or shelf seas. There were no inland or epeiric seas, in contrast to their dominancy during the Paleozoic and less markedly during the Mesozoic. The marine overlaps oscillated back and forth repeatedly and variably in the different areas of invasion, but at no time was more than 6 per cent (Middle Eocene) of the present area of North America under water, while the average for the Tertiary was about 3 per cent or even less. If, however, we include Central America and the Antilles, the total percentage may rise to 10 per cent, with the time of most marked flooding during the Oligocene epoch (Pl. 38).

In Europe and Asia, though the marine overlaps were also less extensive than during the earlier eras, Tethys continued in full extent from western Europe into the Malay region and attained its greatest spread in Oligocene time. Its connections with the Atlantic were limited, and for a time it had Arctic connections east of the Urals. The Alps of southern Europe and the Himalayas of India began to rise in the Miocene and then the eastern half of this extensive middle ocean began to vanish more and more. In the Pliocene, Tethys had attained about the area and the general configuration of the present Mediterranean; but in these alterations the remaining areas of former shallow seas had been changed to a chain of great basins of oceanic depths — an epeiric sea had given way to a mediterranean ocean.

In southern Europe, northern Africa, and Asia Minor the stratigraphic and tectonic history is that of Tethys; in eastern Asia, Melanesia and Australasia, the very intricate record is that of the Pacific. In North America there were marginal pulsations of the Atlantic, the Gulf of Mexico, and the Caribbean, but along the Pacific the history is more in harmony with that of eastern Asia.

Overlaps of the Atlantic Ocean

Cretaceous-Eocene Contacts. — Wherever the contact between the Cretaceous and the Eocene has been seen from New Jersey to central Mexico, Stephenson states that the Eocene sea advanced across a land surface which had reached an old or nearly base-leveled stage of erosion, as is shown by the almost horizontal contacts (see Figs. 491, 492). Of 168 species of Mollusca known in the highest Cretaceous of the Gulf region, not a single species passes into the Eocene.

Northern Atlantic Coastal Plain. — The Cenozoic deposits north of North Carolina (Cape Hatteras) are not at all as well developed as those in the states bordering the Gulf of Mexico, and no Eocene strata are present north of New Jersey. A limited Lower Eocene development of marine greensands and marls not over 225 feet thick occurs in Maryland, Delaware, and Virginia. Upon these follow, after a long interval of land conditions, the Chesapeake Miocene sands, clays, marls, and diatomaceous earth, with a thickness ranging up to 475 feet (see Pl. 38). The Chesapeake formation is of great significance because it has a cool-water fauna that is known to extend all the way from Massachusetts to Alabama, and it indicates that the old north land, Eria, was broken through by Middle Miocene time, permitting an Arctic current to descend along the east coast of North America (see Fig. 501).

Marine Pliocene strata are of very limited and occasional development. All of the Tertiary strata dip toward the Atlantic Ocean, and those of the Gulf States and of Mexico toward the Gulf.

Eastern Gulf Coastal Plain. — From Cape Hatteras southward and westward the marine Tertiary is well represented, with the longest sequence of the older strata in Alabama and Mississippi and of the younger ones in Florida. In the north, toward the old shore, it is a variable series of sands, greensands (glauconite), and marls, with more or less of lignite beds, while in Florida occurs an unequaled development of Oligocene and Miocene limestones and marls, with but little sand. The thicknesses are variable, often under a few hundred feet, and at best attain to over 2000 feet. In Florida the formations above the Eocene reach 2500 feet in depth, and in that state the Oligocene is profuse in invertebrate life. Florida appeared in late Oligocene time as a small island, and has been a peninsula since the Pliocene.

In the embayment of the Mississippi valley extending to southern Illinois occur only Eocene fresh- and brackish-water sands and clays,

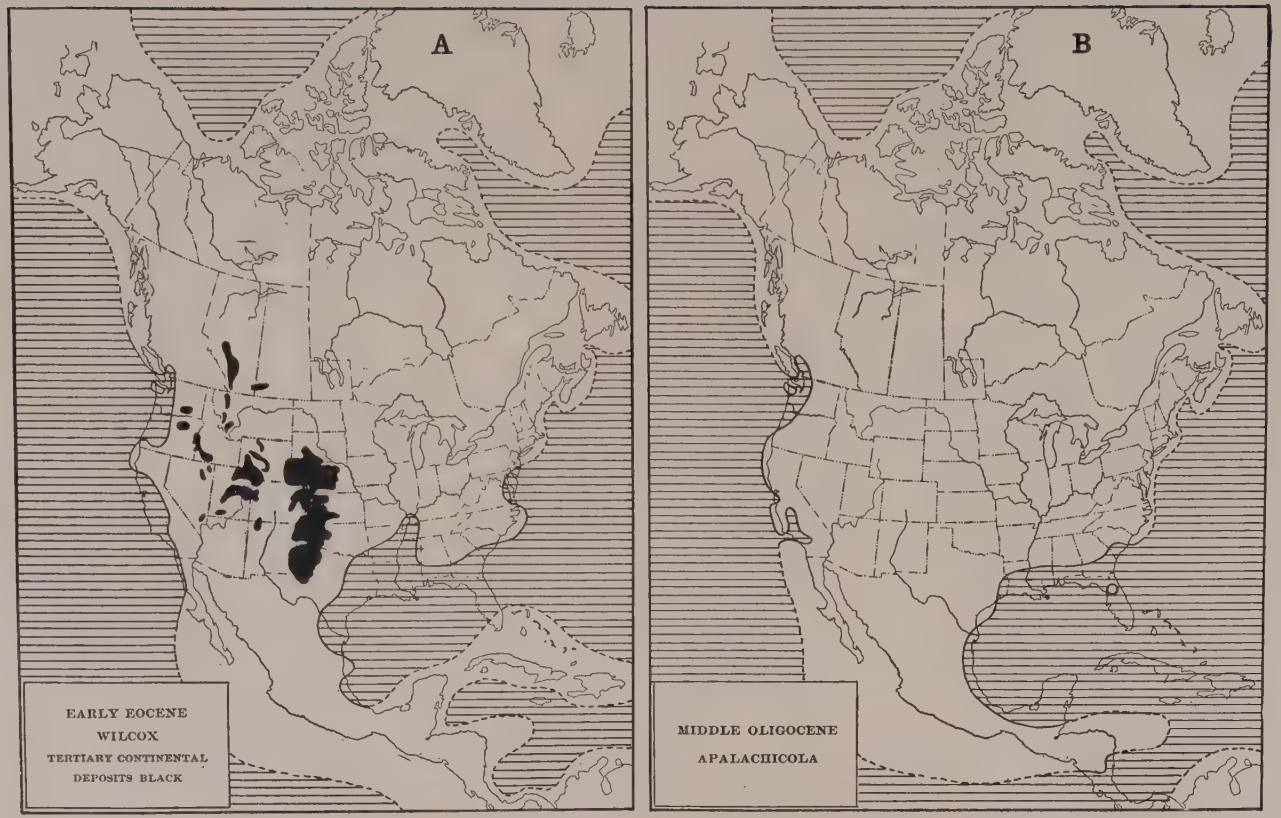


Plate 38. — Tertiary paleogeography.

with beds of lignite, the plant accumulations of former swamps. These are the sediments of the ancient delta of the Mississippi River when the shores of the Gulf of Mexico were at Cairo, Illinois. Later, in early Oligocene time, the sea had withdrawn to middle Alabama (see Pl. 38).

Western Gulf Coastal Plain. — Westward from the Mississippi River, the older Eocene is well developed into Texas and northern Mexico, while the younger Eocene is not known west of the Red River of Louisiana but is again sparingly present in northeastern Mexico. These marine, brackish-water, and swamp deposits of sands, clays, greensands, and lignite beds attain to a maximum thickness of 2000 feet. Since Oligocene time the great stream of fresh water from the Mississippi River has not only had its influence on the sedimentation of this area, but has also prevented the intermigration of the shallow-water life to the east and west of the river.

The Oligocene formations are well developed in Louisiana, where they are essentially fresh-water sands and green clays, reaching a thickness of 1600 feet. In Texas these strata are practically unknown, but in Mexico they occur as narrow overlaps. West of the Mississippi River Miocene strata are known only in deep wells, and at Galveston, Texas, they are 2300 feet beneath the surface, showing the extent to which the eastern margin has been warped beneath the sea since late Miocene time. Of Pliocene strata there is but a small development in Mexico. (See Pl. 38.)

Petroleum of the Gulf Field. — In Tertiary strata of the Coastal Plain in the states of Louisiana and Texas occur a number of scattered, small, circular areas that yield in abundance heavy asphaltic and sulphurous oils (see Fig. 383). It is thought that there are here deep-seated bathyliths that deflect upward hot waters which dissolve out the disseminated salts of the lower beds. Ascending, the waters cool, crystallizing out the salts, which form concretionary rising plugs bulging the higher beds into domes, and in these local arches the oil rises and accumulates. (Harris.) (See Fig. 499.)

Central America. — There are no marine deposits of the early Eocene known in Central America, and hence we may assume that at that time and during the late Cretaceous North America and South America were united by a land bridge wider than the present one. This connection permitted the land life of the two continents to intermigrate. During later Eocene time, however, and more especially throughout the Oligocene, the Caribbean Sea spread widely across southern Central America and some of the Atlantic Eocene molluscs migrated to California. In Miocene time the two continents were again united, but even though the Central American land was wide,

Fig. 499. — Burning oil fountain, 330 feet high, in Miocene strata at Baku, Russia. In 1897 this well was yielding, through a 12-inch pipe, 90,000 barrels of petroleum per day.

the land bridge does not appear to have been a favorable one for intercontinental migration of land animals. This may have been due to the mountainous and volcanic nature of the region, but more probably to the barrier of the tropical jungle. The Caribbean did not again invade this land until Pliocene time, and then only marginally. (See Pl. 38.)

Antillian Region. — The Greater Antilles, Cuba, San Domingo, and Porto Rico appear to have been large land areas during the Eocene, and it further seems that Cuba was then connected with Central America. In the Oligocene, however, all except the mountainous central portions of these islands were beneath the sea, whose waters were tropical and abounded in a very varied life. The record begins with local shallow-water formations of dark to black shales and ferruginous sandstones up to 1000 feet thick. These are followed by the widely spread white foraminiferal limestones and marls varying in depth from 700 to 2600 feet. From this it appears that it was during the Oligocene that the oceans most widely flooded the Antilles and Central America.

Elevation of the Antilles again took place early in the Miocene, but it is not yet established that Cuba was then or at any time subsequently in connection with Central America. The living native mammals of the Antilles are small, of but a few kinds, and of ancient types. None of the larger North or Central American mammals appear to have reached these islands. In the Pleistocene of Cuba, however, there are several species of ground-sloths that Matthew states are all derived from a single small form thought to have drifted there on a natural raft across the Caribbean from South America.

Overlaps of the Pacific Ocean

Almost all of our knowledge of marine Cenozoic invasions along the Pacific is restricted to the states of California, Oregon, and Washington, and northward into the Vancouver area of Canada. There appears to be no sedimentary record along the shores of British Columbia and Alaska until late in Miocene times, and even this marine overlap was of small extent (see Pl. 38).

In most places the Cenozoic rests unconformably upon the Mesozoic or older rocks, though at times the contact is a disconformable one. In California there is another unconformity in the Miocene. Arnold states that about 25,000 feet of strata were accumulated during the Cenozoic, but if we take the maximum thicknesses for all the formations the total rises to about 45,000 feet. In the main the deposits are coarse detritals, as sands, muds, and much volcanic ash with local lava flows. The seas were shallow and in places became filled with sediment and then passed into marshes, making coal beds, as was especially the case in the estuary of the Puget Sound region, where 125 coal beds occur. The times of most marked and general sedimentation were in the early Eocene (8000 to 12,000 feet) and the

late Miocene (8000 feet in California). In the Pliocene and Pleistocene, 13,000 feet of sands and volcanic materials were laid down south of San Francisco.

Throughout Alaska and extending into Mackenzie and British Columbia occurs the wide-spread Kenai formation of continental character, which has a maximum thickness of 10,000 feet. It has much plant material and many beds of lignite, with some marine animals that indicate the age to be Eocene.

It is not yet clear to what extent during the Cenozoic Alaska was united with Siberia, though it seems that the ocean did not invade the Bering Strait region until late in Miocene times. If this land bridge between Asia and America was not in continuance throughout all of this time, it was during most of the era. Since the Pliocene the bridge has been crossed by the sea at different times, though at no time was this very shallow sea much deeper than it is now.

Petroleum in California. — California is now the leading oil-producing territory in North America, the yield being 38 per cent of the total amount produced by the United States (see Fig. 383). The total acreage is not over 125,000, and in 1914 there were more than 5800 producing wells, with a depth of from 200 to 5700 feet. The petroleum is from more or less decidedly deformed strata ranging in age from Cretaceous to Pliocene, and the oils are mainly asphaltic, though lighter ones also occur. (Arnold.) (See Fig. 499.)

Continental Deposits of the Rocky Mountains

Fresh-water and eolian deposits of Tertiary time cover great areas in the United States, chiefly in the foothills and the plains country east of the Rocky Mountains (see Pl. 38, Fig. A). It should be clearly understood, however, that the deposits consist of a large number of separated formations, laid down by many large and small rivers over their flood plains, now here and now there throughout the Tertiary. As a rule, the strata remain horizontal and are somewhat consolidated into sandstones, sandy shales, and local conglomerates. Volcanic ash in thick beds or reworked by water and wind occurs in most of the formations and constitutes a considerable amount of the Tertiary rocks of the plains country. Nearly everywhere the strata are exposed to view in more or less locally dissected places where the rain, streams, and wind of the present semiarid climate have worn them into those picturesque areas known as "bad-lands" (see Fig. 21). The thickness at any one place varies from a few hundred feet to several thousand but if all the thickest local deposits are combined the total Tertiary sedimentation attains to well over 20,000 feet. It is in this vast mass of material that lies buried the most interesting known record of mammalian evolution, the remains of one organic

dynasty after another, whose histories have attracted the attention of paleontologists the world over.

The older geologists stated that these strata had in the main been laid down in lakes of vast extent. During the past fifteen years, however, it has been shown that they are the materials of rivers originating in the mountains, and meandering and unloading over great flood plains under a more or less semiarid climate. In addition there is also a great deal of wind-borne material, desert dust, and fine volcanic ashes from the western volcanoes, that at times killed and buried the flora and fauna over considerable areas (see Fig. 506).

Paleocene. — During the quieter time between the Laramide Revolution toward the close of the Cretaceous and the renewed Eocene elevation were laid down the widely distributed Paleocene deposits (Fort Union, Puerco, Torrejon), with thicknesses ranging between 1000 and 2000 feet.

Eocene. — Then followed, in the west, uplift combined with much volcanic activity, causing the development, during the early Eocene, of intermontane formations (Wasatch, Wind River, Green River of shallow lake origin, and Bridger basins). These have thicknesses varying from 2400 to over 10,000 feet, the greater part of which consists of ash and coarse igneous detritals. In later Eocene times (represented by the Uinta basin) the formations are much thinner, averaging about 2000 feet. The Eocene has the best developed record of the Tertiary and its formations occur in western Wyoming, eastern Utah, and western Montana.

Oligocene. — In Oligocene time (White River formation, John Day basin of Oregon consisting largely of from 3000 to 4000 feet of volcanic ash and tuffs) there was little crustal disturbance throughout the Cordilleran region, and therefore the deposits do not as a rule average much above 500 feet in thickness. They are, however, of wider distribution than are the Eocene deposits, occurring in Nebraska, North and South Dakota, Wyoming, Colorado, and Montana. The formations consist of fine sands, sandy muds, and considerable fine ash derived from the far away western explosive volcanoes. There are also local thin limestones rich in fresh-water snails, the deposits of ponds and small lakes.

Miocene. — The general environment of the Oligocene was continued into the Miocene (Arikaree, Harrison, Lower Loup Fork, Clarendon, Deep River formations), with the difference that elevation was again going on west of the plains country in later Miocene time, along with a change to a cooler climate. There is also more ash present and the grain of the strata is coarser in the west and finer in the east. The thickness of the formations varies between 400 and 2300 feet, with the main areas of deposition in Nebraska, Kansas, and northeastern Colorado.

Pliocene. — The Pliocene formations (Upper Loup Fork, Blanco) are widely scattered, of limited extent, and not very well understood. The climate became more arid and much cooler and most of the larger mammals were exterminated.

Cascadian Revolution

North and Central America. — In the preceding chapter it was stated that the Mesozoic era in North America was closed by the Laramide Revolution, when the Laramide Mountains (practically the

Rocky Mountains) were folded and faulted toward the east (see page 900). During Paleocene time mountain making was not active in the area of the Laramides, but at the close of this epoch, folding, faulting and igneous activity were again very marked in Utah, western Wyoming, and Montana. Eruptions, mainly of an explosive character, then continued, though with diminishing force, throughout Eocene and Oligocene time, but the earth-shell remained fairly stable, enabling the atmospheric forces to reduce greatly the high elevations of the Laramide Mountains.

In Middle Miocene time the Pacific States were again in the throes of mountain making, and igneous eruptions became active, with the formation of high local mountains in eastern Washington and Oregon, and of the Coast Range of California (see Fig. 501). It is interesting to note here that the great earthquake rift of San Francisco which extends for more than 400 miles southeast into the Mohave desert had its origin at this time. Of active volcanic regions during the Miocene and Pliocene, there were eleven, extending interruptedly from southern Mexico into Alaska. In the basin of the Columbia River more than 200,000 square miles were covered by lava flows, ranging in depth up to 4000 feet, and this area is to-day the Columbia River Plateau (Fig. 482). A more scenic area of igneous rocks is the Yellowstone National Park, where the ashes and other material extruded from Miocene volcanoes buried forest after forest, and where many of the still vertical trees are changed to silica, though preserving their original microstructure (Fig. 500).

During the Miocene, decided folding and faulting with volcanic activity also occurred in the Isthmus of Tehuantepec of southern Mexico, in Central America, and apparently throughout the West Indian islands. Finally, it may be said that especially during the Miocene, and less in the Pliocene, the entire area of the overlaps of the Pacific Ocean in North America (see Fig. 482) was being elevated, folded, faulted, and thrust eastward into the Pacific system of mountains. During the Pliocene, the entire area of the Rocky Mountains and especially the plateau region of the Colorado River were further vertically elevated several thousand feet. With this elevation the Colorado River region began to cut its great gorge and since then has been developed what is now the grandest geologic exposure anywhere, the Grand Canyon of the Colorado (Fig. 349). With these wide-spread movements in the earth-shell also came into being those grand volcanoes that were still active throughout the Pleistocene: Rainier (14,526 feet above the sea), Shasta (14,380 feet, see Fig. 153), and Lassen's Peak (10,437 feet) of the Pacific States;

Popocatepetl (17,500 feet), Ixtaccihuatl (16,900 feet), and Orizaba (18,250 feet) of southern Mexico.

Eastern North America was also elevated at this time, but how much is not yet determined, and the entire Mississippi valley was

Fig. 500. — Miocene tree trunks of the Fossil Forest, Yellowstone Park, Wyoming. Photograph by J. P. Iddings, U. S. Geol. Surv.

raised several hundred feet, or to its present elevation. Generally speaking, the close of the Pliocene must be regarded as a time of great deformation, a critical period in North American geologic history.

South America. — Toward the close of the Cretaceous, the Andes had been elevated and folded throughout the length of South America (4500 miles), and during most of Tertiary time an extensive peneplain (in places it was a postmature surface) was being developed in the Central Andes. Vertical uplift began in later Tertiary time, elevating this peneplain from 3000 to 7000 feet. This was in turn eroded to mature slopes and then was rapidly warped in Pliocene and early Pleistocene time, so that now the deeply dissected erosion surface of the old peneplain stands at an average elevation of 12,000 feet, though locally it varies between 6000 and 15,000 feet. Upon it in the west rest immense lava flows and lofty volcanic cones, some of which attain a height of 21,000 feet above the sea. These are part of a great volcanic field whose development began in the early Tertiary and was completed soon after the Pliocene uplift began. The Central Andean plateau is the second highest in the world, being exceeded only by that of western Tibet to the north of the Himalayas of India, where the intermontane plains range from 14,000 to 17,000 feet above the sea. (Bowman.) (See Fig. 501.)

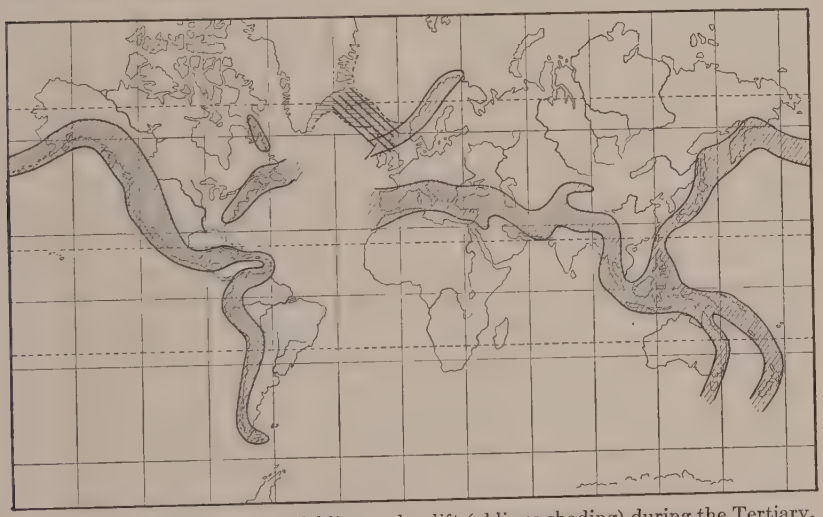


Fig. 501. — Areas of dominant folding and uplift (oblique shading) during the Tertiary. Horizontal shading, the fractured and down-sinking area of Eria; northwest-southeast lines, the general direction of fractures and dikes.

Greenland. — All Greenland and the region eastward across Norway, Sweden, and Finland (Fennoscandia) were subject to great block faultings or warpings previous to the Pliocene, developing not only great rifts or graben but broad sinking areas as well, with a general trend to the northwest and southeast. This was the time

when Eria was broken through, separating Laurentia from Baltica (Fig. 501). Previous to the Middle Miocene this land was the bridge that enabled the mammals of Europe and North America to intermigrate. Periodically, but more especially during the Oligocene and Miocene, lava flowed widely through fissures over all these lands, the Faroe Islands, Scotland, and western Ireland (Giant's Causeway). The foundering of the crust where the Norwegian sea now is, permitted the triumphant spread of the Atlantic into the Arctic Ocean.

Gondwana. — On page 880 it was stated that Africa was separated from South America late in Comanchian time (Fig. 488) and now we learn that late in the Eocene the remainder of this equatorial Atlantic bridge sank, since Eocene deposits are general along the western border of Africa. The Cretaceous remnants of Lemuria almost all sank beneath the Indian Ocean during the Tertiary.

Europe. — The majestic Alps of Europe are mute evidence of the great unrest of the earth's crust during the Cenozoic, their upward culmination taking place in Pliocene time. The movement began in the west late in the Oligocene, when the Pyrenees of Spain, the Rif Mountains of Morocco, and the Apennines of northern Italy had their origin. The entire Alpine system of western Europe began to rise early in the Miocene, and this deformation was most active late in the same epoch and was completed early in the Lower Pliocene when these mountains stood at their highest. The Eocene nummulitic limestones of the Alps are still found 10,000 feet above the sea, and those of the Pyrences 11,000 feet. The movement was both vertical and thrusting from the south and southeast, from the southern portion of Tethys, elevating and folding the Tertiary and older strata of the northern areas of this mediterranean into overturned, recumbent, and nearly horizontal folds, and pushing the southern or Lepontine Alps about 60 miles to the northward into the Helvetic region. Erosion has since carved up these overthrust sheets, leaving remnants lying on foundations which belong to a more northern portion of the ancient sea. Most noted of these residuals of overthrust masses is the Matterhorn, a mighty mountain without roots, a stranger in a foreign geologic environment. The thrusting was felt as a warping as far northwest as London, for the basins of London and Paris date from this time. The Caucasus Mountains of eastern Europe, between the Crimea and the Caspian Sea, are also of early Pliocene origin, for their Miocene strata are now 6500 feet above the sea (see Fig. 501).

Himalayas of India. — During Eocene time Tethys continued unbroken across Asia Minor, northern India, and Burma into the

Indian Ocean and Melanesia. At the close of the Eocene, however, all of the Tethyian area of the Himalayas and Burma began to fold, giving rise to mountains of considerable altitude in many regions, and yet not extensive enough to blot out the sea. During the Oligocene, Tethys, even though shallow, still preserved its continuity, accumulating thick, uniform, marine deposits of gray to greenish shales and calcareous sandstones (Flysch of Swiss geologists). Toward the close of the Middle Miocene, the second and more marked phase of folding began, changing Tethys into a series of disconnected but subsiding basins, accumulating the continental deposits known as the Siwalik clays, sandstones, and conglomerates. Finally, in the Pliocene, came the third and greatest upheaval, when the Himalayas, the loftiest mountains of the earth, had peaks nearly as high as Mt. Everest of the present, which stands 29,002 feet above the sea. The nummulitic limestones of Eocene age are even now as high as 19,000 feet above sea-level, and once extended higher over the mountain axes. This uplift affected the land to the north for 1400 miles into Tibet and Mongolia, and the thrust pushed the older rocks over the newer ones in a north to south direction. (Vredenburg.) (See Fig. 501.)

Summary. — In North America the deformation of the Laramide Revolution was renewed in the early Eocene, followed by a long, almost quiescent time up to the close of the Oligocene. Then unrest made its appearance in the western area of Tethys, and throughout the later half of Miocene and Pliocene time mountain making was going on in most parts of the world, in many areas on a stupendous scale. North and South America with their longitudinal chains of mountains did not change much in outline during the Tertiary, but Europe, Asia, the Antilles, and Central America, with their latitudinal foldings, underwent marked alteration, and it was in fact in the Pliocene that these continents took on their modern expression. Finally in the Pleistocene the greater part of the Pacific Ocean was margined by majestic volcanoes.

The Cascadian Revolution of western North America has been of long duration, beginning in the Middle Miocene and continuing into the present time. It is marked by intermittent action, pulsations of folding, thrusting, and igneous activity, resulting in new mountain systems, increasing relief, and a higher continent. To us it now appears as if interrupted and finished, because we see it in near perspective. In its entirety, however, it is one of the greater revolutions of the earth, and there is no proof that the end has yet been attained. Long ago Le Conte said that the Cascadian Revolution is

so recent that the record of it is not lost, and a study of it enables us better to comprehend the changes wrought by the earlier revolutions. In the geologic future it will take its place in the earth record through the evidence of its great foldings, metamorphism, and wide erosion of the older record — a transformation comparable to that wrought by the Appalachian Revolution closing the Paleozoic.

The closing revolution of the Tertiary era was a critical period in the history of the earth, and as it culminated in the Pleistocene glacial climate, the conditions were all the more hazardous for the organisms that inhabited the polar and temperate regions of the earth. The warmer parts of the globe were the asylums that repeopled the northern lands, but man, probably arising in Asia, advanced from the savage to the civilized state under the influence of cooler and even glacial climates. We are now living in a time of rugged lands, obliteration of ancient peneplains, cold polar climates, and marked temperature belts.

CHAPTER LIII

THE EVOLUTION OF MAMMALS AND THE RISE OF MENTALITY

Origin of Mammals. — The lands of Cenozoic time were dominated by mammals, and the seas and oceans of this era were not devoid of them. Mammals were, in fact, as characteristic of the Cenozoic as reptiles were of the Mesozoic. It is, however, true that mammals originated as early as the Triassic, but at no time in the Mesozoic era did these small animals take the lead among organisms.

It was pointed out on page 810 that the mammals had their origin in reptiles (Theriodontia) that lived during Permian and Triassic times. These were long-limbed quadrupedal forms with a mammal-like skull and teeth, and among them were insect-eating types that are thought to have given rise to the egg-laying mammals. These small reptilian mammals first appeared in the Triassic, but though they lived throughout the Mesozoic, little is known of them. In fact, our knowledge is almost restricted to lower jaws and isolated teeth and it is not until we reach the Cenozoic that skeletons become sufficiently abundant to determine their structure and their genealogies. This higher mammalian succession is a wonderful series of evolutions, and if the student wishes to follow it out in more detail than can be given here, he is referred to Scott's *A History of Land Mammals in the Western Hemisphere* and Osborn's *The Age of Mammals.*

Definition of Mammals. — Mammals, structurally the highest group of animals, are warm-blooded vertebrates with glands that secrete milk when the females are nursing young. These glands, which vary in number from one to eleven pairs, are the mammary glands or breasts, the structures from which the class has taken its name, for *mamma* means *breast.* They are also present in the males, but are rudimentary and normally non-functional. All mammals are more or less covered with hair and these growths of the skin are as characteristic of mammals as feathers are of birds.

With regard to the nervous system, the brain in mammals attains the highest degree of development known, and is most markedly convoluted in man. The body cavity differs from that of all other

vertebrates in that it is completely divided into two parts by a muscular membrane, the diaphragm, which separates it into a thoracic cavity containing the heart and lungs, and an abdominal cavity containing the remaining viscera. In most mammals there are two sets of teeth, the milk dentition or temporary teeth which eventually fall out, and the permanent teeth which succeed them. The heart is four-chambered as in the other class of warm-blooded animals, the birds, and the course of the blood through it is the same in both. The period of fœtal development or gestation varies from three weeks in some mice to twenty months in the elephant.

Most mammals have a completely terrestrial habitat, while the seals, sea-lions, sea-cows, whales, and porpoises live in the oceans. One order of wide distribution, the bats, have developed the front limbs into wings, while other stocks have lateral or body membranes between the limbs, and spreading these, glide from tree to tree.

Classification. — There are living more than seven thousand kinds of mammals, and in North America alone there are more than twenty-one hundred species. Of fossil mammals there are several thousand additional kinds. All these are separated into two subclasses on the basis of the development of the young. In the most primitive mammals, the *Prototheria*, the young are not born alive but are hatched from eggs as in reptiles and birds. Of this ancient stock there are but few living representatives, among them the duck-billed mole (*Ornithorhynchus*) and the spiny ant-eater (*Echidna*) of Australasia. These were once distributed all over the world, particularly in Mesozoic time (Protodonta).

In the other subclass, the *Eutheria*, the animals are viviparous, and the group includes nearly all the living mammals as well as those of Cenozoic time. The marsupial mammals (Didelphia) or animals with an abdominal pouch are the more ancient and primitive, though more advanced than the egg-laying Prototheria. In nearly all of them there is no placenta (see page 807). The young are born in an immature state and are then attached by the mother to the breasts in the marsupium, where they complete their development. They had their origin early in the Mesozoic (Allotheria, also known as Multituberculata), were widely distributed throughout the world, and died out with the Paleocene. Out of these little animals arose other marsupials, probably as early as the Jurassic, and it is thought that they in turn gave rise to the living forms. The marsupials are still in full development only in the ancient organic asylum, Australasia, though the opossums are common to North and South America.

By far the greatest number of living and Cenozoic mammals are the placental forms (Monodelphia). The placenta is a special growth, partly of fœtal and partly of maternal origin, by means of which the embryos are attached to the mother and nourished during the period of gestation; the young are born in a relatively mature state. The placental mammals appear not to have arisen in the marsupials, but to have had an independent origin in the egg-laying forms (Prototheria) during the Mesozoic.

There are at least twenty-seven orders of placental mammals, and of these but sixteen have living representatives, the others having originated in and died out with the Cenozoic. Among the *clawed mammals* (Unguiculata) the more con-

spicuous orders are the Carnivora or beasts of prey (wolves, bears, cats, seals, walruses); Rodentia or rodents, the gnawing mammals (hares, rabbits, squirrels, beavers, rats, mice, porcupines); Chiroptera or bats; Edentata or sloths and armadillos; and Insectivora or insect-eaters (moles, hedgehogs, shrews). The *mammals with nails* include but one order, the Primates, such as the lemurs (Lemuroidea), and the monkeys, apes, and man (Anthropoidea). The *hoofed mammals* (Ungulata) are very varied, and among them may be mentioned the even-toed forms (Artiodactyla), such as the swine, camels, deer, antelopes, sheep, oxen; the odd-toed forms (Perissodactyla), such as the horses, tapirs, rhinoceroses; the trunk-bearers (Proboscidea), the elephants and mastodons; and the Sirenia or sea-cows and dugongs. Mammals wholly adapted to the oceans and therefore greatly altered in form so as to resemble fishes are known collectively as Cetacea (whales, dolphins, porpoises).

Increase in Size of Brain. — Lartet suggested in 1858 and Marsh demonstrated in 1874 and again in 1885 that the brain in mammals increased in size throughout the Cenozoic, and that the enlargement was by far the most striking in the upper lobes or cerebrum. In the Eocene the brain was about one eighth that of living forms of the same stocks.

Mammal Succession in North America

The Tertiary of North America opens with an archaic indigenous mammal fauna, a most curious, strange, and bizarre assemblage. It is plain that it is an advanced and diversified fauna, the descendants of Mesozoic mammals. Later appear unheralded as migrants the modern mammals, and their introduction sounds the death knell of the archaic forms, for one stock after another vanishes and most of them are gone before the close of the Eocene, though the ancient flesh-eaters (creodonts) continue into the Oligocene. Where the modern mammals originated is not yet known, though it is usually assumed that Asia was their birthplace.

Paleocene Mammals. — The North American Paleocene mammals were all archaic, that is, they were very primitive, generalized, omnivorous or fruit-eating, dominantly placental, and small. None of them were as large as a sheep, the limbs were short, with five digits each, the tails were long and heavy, and the brains extremely small. They were closely related to one another and appear to have been the direct descendants of the Mesozoic mammals continued with some change into the Cenozoic. There were among them no known representatives of the primates, rodents, carnivores, or of the even-toed and odd-toed hoofed mammals. Of modern orders, only the insectivores and marsupials were represented.

Lower Eocene Mammals. — The most striking feature of the life of early Eocene time (Wasatch-Wind River) was the appearance in

considerable numbers, both in western Europe and in North America, of the first representatives of the progressive or modernized mammals. Among them were diminutive horse-like forms (*Eohippus*), fleet-footed rhinoceroses, tapirs without a proboscis, the first ruminants and pig-like forms, squirrel-like rodents, insectivores reminding one of the European hedgehogs, carnivores, lemurs, monkeys, and probably also marsupial opossums. It was in the main the mammalian life of a mountainous country, superior in foot and tooth structure to the indigenous archaic fauna, and of a higher intelligence. In the struggle for existence the archaic mammals were the losers (58 per cent present in the Wasatch) and before the close of the Lower Eocene their number was far less (Wind River, 37 per cent).

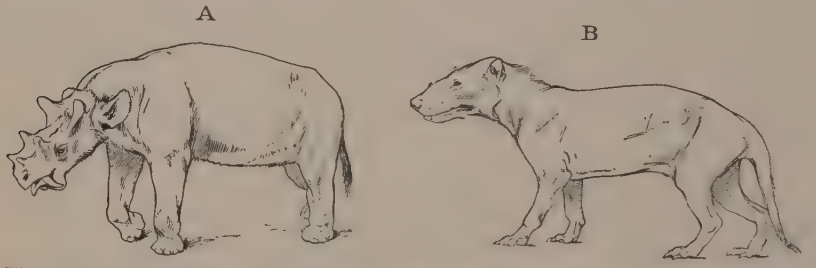


Fig. 502. — *A*, large hoofed uintathere (*Uintatherium alticeps*) of the Eocene (Bridger). From Scott's *History of Land Mammals*. *B*, the last creodont (*Hyænodon*) of the Oligocene. From Osborn's *Age of Mammals*.

Middle and Upper Eocene Mammals. — In the great abundance of mammals in the later Eocene there was no evidence of new migrants having come from Asia or Europe, but the fauna was dominantly that of the older Eocene with a small proportion of archaic forms (Bridger, 20 per cent; Uinta, 13 per cent), continued with persistent and divergent evolution. The changes were largely toward greater size, more muscular power, and the origination of new indigenous forms. There were many hoofed animals and all were browsers. This was again an upland or mountainous mammal assemblage, on the whole well balanced, with an equal distribution of arboreal, running, aquatic, burrowing, carnivorous, and herbivorous types.

During the later Eocene appeared tiny camels, true tapirs, oreodonts (an extinct group of ruminating hogs peculiar to America, Fig. 506), giant pigs or entelodonts (Fig. 504), armadillo-like animals with leathery shields, and primitive dog-like forms. In addition there were many hoofed forms, as titanotheres (Fig. 503) and the very characteristic gigantic uintatheres (Fig. 502 *A*) — mammals unlike anything now living — and fleet-footed rhinoceroses. The archaic

flesh-eating creodonts were still present (Fig. 502 *B*). Marsupials were represented by the opossums, and the lemurs and monkeys were still common, though representing the last of the primates in North America.

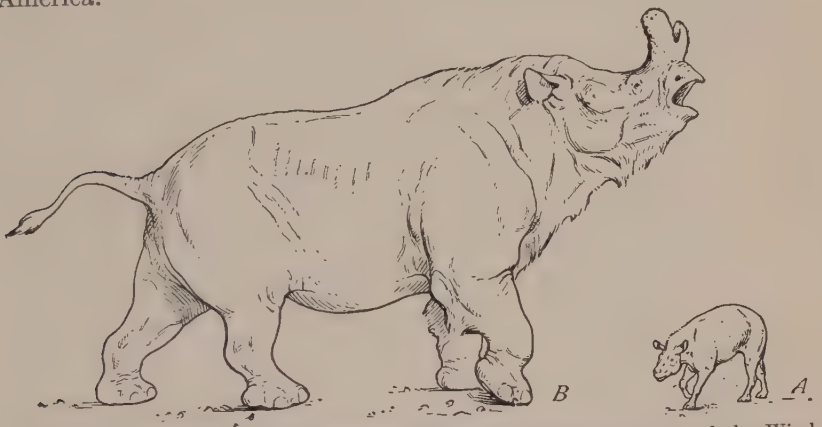


Fig. 503. — Titanotheres. *A*, first stage in the evolution (*Eotitanops* of the Wind River). *B*, last known stage (*Brontotherium* of the White River). After Osborn.

Oligocene Mammals. — It was during the Oligocene that mammals for the first time took on a modern aspect, for here nearly all were progressive forms. We now begin to get representatives also of still existing families, and of such there were six of rodents, four of carnivores, and one of odd-toed hoofed mammals. Then in this period we get our first knowledge of the varied mammalian life of the open plains and of grazing mammals, indicating that the grasses were taking possession of the open country.

Fig. 504. — One of the giant pigs or entelodonts (*Archæotherium*) of the Oligocene (White River). From Scott's *History of Land Mammals*.

Early in the Oligocene took place a second and more marked invasion from Europe. The interchange was considerable, yet it was not complete and the time of migration was of short duration. Europe lost its horses early in the Oligocene, but in North America there was continued evolution of the three-toed forms. The camels were also better represented (Fig. 507), and among them were grazers, these and other hoofed mammals being present in bewildering variety. The tapirs were not common, but of rhinoceroses there were many, some fleet of foot, some stocky, heavy and amphibious in habit, and of the true rhinoceroses there were forms with and without horns.

Rodents were also common, such as beavers, squirrels, pocket gophers, mice, and hares. Among the ruminants, peccaries were numerous, the entelodonts were of large size (Fig. 504), and the oreodonts, not unlike the peccaries and wild boars in appearance and size, were exceedingly abundant, varied, and ran in great herds (Fig. 506). Among the carnivores, small dogs were remarkably abundant and diversified, in fact, more so than ever before or since. The last of the archaic creodonts occurred here (Fig. 502 *B*) and as they vanished their place was taken by dogs and later by wolves and the first sabre-tooth cats; true cats, however, were not yet present.

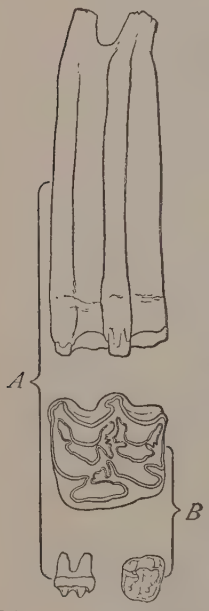


Fig. 505. — Grinding and grazing teeth. Below, grinding teeth of the "dawn horse" (*Eohippus*); above, grazing teeth of the living horse (*Equus*). Drawn to scale, to show the increase in complexity, length (*A*), and width (*B*). From Osborn's *Age of Mammals*.

Miocene Mammals. — Miocene mammals are replete with interest because of the changes wrought in them and in the floras by the alteration in climate to cooler and semiarid conditions. Great chains of mountains were being elevated, Eria was being torn apart (see page 923), and these derangements in the topography and geography had their effects not only on the climate and life, but on the migrations of the mammals as well. The Miocene, and especially the later Miocene, was therefore characterized by an increase of grassy plains, though this statement is not based on the presence of fossil grasses but is deduced from the change that took place during this period in the mammalian teeth from those of the browsing type to the grinding or grazing kinds (Fig. 505). There were now large numbers of horses, camels, ruminants, and rodents with high-crowned, persistently growing, grinding teeth. On account of the silica which the grasses contain, they are very abrasive and rapidly wear the teeth down.

The third marked migration of mammals into North America took place in the Middle Miocene and the migrants came from Asia by way of the Siberia-Alaska bridge. The most conspicuous among them were the four-tusked, browsing, long-faced mastodons, the short-legged rhinoceroses, the cats, and the beavers.

Prominent among the Miocene mammals were the horses, which roamed the plains in great herds. All were three-toed and at first all

were still browsers, but in the later Miocene the grazing type predominated. Camels were also plentiful. Rhinoceroses were present in great variety, some hornless, others with a single horn on the end of the nose, and still others with an additional horn on the forehead. The commonest type were extremely heavy, with very short legs (*Teleoceras*); others were long in the legs and less massive in body.

Fig. 506. — A remarkable group of three Miocene oreodonts (*Promerycochærus carrikeri*). Above are the skeletons as found in the rocks (note how they are huddled together, having met death in this attitude), and below, the animals restored in the flesh. Found by O. A. Peterson in Sioux County, Nebraska. Originals in the Carnegie Museum, Pittsburgh, Pennsylvania.

Peccaries abounded, and the last of the giant pigs, the entelodonts, were present, one of them, in the Lower Pliocene, being over 6 feet tall (*Dinohyus*). The oreodonts were still common (Fig. 506) but after the Middle Pliocene declined rapidly. The first true deer appeared in the Lower Miocene and in addition there were hornless deer and antlered deer-antelopes that were slender and graceful little creatures.

Among the carnivores, the dog kinds were in great variety, some small, others as large as the largest bears. True cats appeared here for the first time, and the sabre-tooth tigers were plentiful though not large. There were also weasels, martens, otters, and racoons, but no bears are known in America before the Pleistocene.

Pliocene Mammals. — Of Pliocene mammals not much can be said because strata of this age are scarce. The continent stood high and was undergoing elevation in the western portion, with the result that the rivers carried into the sea their loads of sand and mud.

Probably the most interesting animals were the great ground-sloths and the glyptodonts (Fig. 514), because they came from South America among the migrants that traveled north over the Central American connection established in Miocene time. From the north there radiated over the same land bridge into South America in Pliocene time large sabre-tooth tigers (*Smilodon*), large cats, dogs, racoons, horses, llamas, deer, mastodons, tapirs, peccaries, etc.

Of mastodons there were several species in the Pliocene of North America; the horses, in considerable variety, were still three-toed; llamas and the tallest of giraffe-like camels continued to live; rhinoceroses with and without horns were present; sabre-tooth tigers and true cats existed, some of them as large as the lion.

Euroasiatic connection with North America is again indicated by the migration of American camels into China and India during the Pliocene. At the same time the hollow- and twisted-horned antelopes came into America.

Evolution of the Camels

Origin. — The family Camelidæ, including the llamas, guanacos, and camels, now restricted to the desert areas of central Asia and the colder parts of South America, had its origin, strange as it may appear, in the Upper Eocene of North America and a complete development there in the Tertiary. The llamas began to spread southward through the tropics into South America in the Pliocene and at the same time the camel stock radiated northward through cooler climes and across the Alaska-Siberia land bridge into Asia and Africa. Large camels were still plentiful in North America during the earlier half of the Pleistocene, but became extinct near the middle of this time.

Distinguishing Characters. — In the more recent members of the Camelidæ the legs and feet are very long and there are but two digits (even-toed = Artiodactyla) on each foot, the third and fourth, which bear hoofs. These, however, do not support any weight of the body

and are no more than nails. Beneath the feet in living camels there is a single broad pad, and in the llamas there are two separate pads of elastic tissue that bear the weight of the animal. The great single hump in the living dromedary and the pair of humps in the living Bactrian camels consist of fat. These do not impress themselves upon the skeleton and one can not therefore tell whether or not the fossil forms of the family had such humps. The long neck is always made up of seven vertebræ.

The Camelidæ are ruminants or cud-chewers of vegetable food. This is passed from the gullet into the first chamber of the stomach, then into the second, and after a time goes upward through the gullet again to the mouth, where it is remasticated; then it passes to the third and finally to the fourth or true stomach, where gastric digestion takes place.

Evolution. — Scott, from whom the following is largely taken, states that the mode of evolution shown by the camels differs in no significant regard from that seen in the horses. There was the same increase in bodily stature and in the relative lengths of limbs and feet, a diminution in the number of digits from the original five to two (3 and 4) in camels (Fig. 507), and to one (3) in horses (Fig. 508), and a similar development of the high-crowned grinding teeth from the low-crowned browsing type. The two families of camels and horses each arose in a single series. This monophyletic condition continued through the Eocene and most of the Oligocene, but in the later Oligocene and more markedly in the Lower Miocene the camels and horses branched out, each in their own fashion. In a general way, they kept quite an even pace in their advance from the more primitive to the more specialized condition.

Geologic Succession. — The camels may have had their origin in the Lower Eocene (Wasatch) in a tiny creature even smaller than the domestic cat (*Trigonolestes*), which probably had five toes on each foot. A little later (Middle Bridger), however, is found an animal (*Homacodon*) that appears to be a member of the camel family, a creature but little larger than the preceding. The head was cameline in appearance, but each foot had four functional digits (2, 3, 4, 5).

In the Upper Eocene (Uinta) occurs a camel hardly larger than a jack-rabbit (*Protylopus*, Fig. 507 *C*, *G*). The front limbs terminated in four functional digits of nearly one size, but in the hind legs there were but two functional toes, with two tiny dew-claws. In the Oligocene (White River) there was a continuous series of these animals (*Poëbrotherium*, Fig. 507 *A*, *D*, *H*), increasing in size to about that of a sheep, but of much lighter build, with small, pointed, cameline heads, relatively long necks and bodies, and long, very slender limbs and feet. The limbs were of nearly equal length, each terminating in two separate digits and nodular vestiges of two others, and deer-like hoofs. This type of foot then persisted into the Lower Miocene. In the Lower Oligocene there is indicated but

a single generalized phylum of camels and from it diverged three lines, each one of which evolved into different camel-like animals. First were given off the giraffe-camels, so called because they resembled and fed like giraffes (Fig. 507 *B*); at about the same time originated the short-lived gazelle-camels (*Stenomylus*),

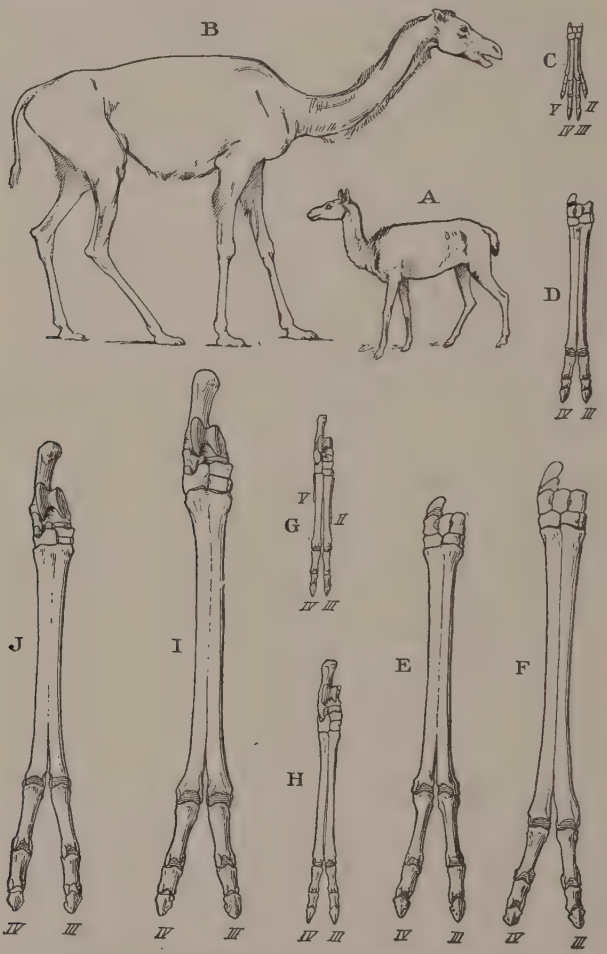


Fig. 507. — Evolution of the camels. *A*, the ancestral camel (*Poëbrotherium*). *B*, primitive giraffe-camel (*Oxydactylus*). *C-F*, right hand of a series of progressively younger camels (*Protylopus* of the Uinta, *Poëbrotherium* of the White River, *Procamelus* of the Miocene, and the living guanaco). *G-J*, right foot of the same series. *B* from Osborn's *Age of Mammals*, the rest from Scott's *History of Land Mammals*.

which were delicate in build; and finally arose the long-lived main stem which bifurcated into two phyla, the llamas and the true camels.

The giraffe-camels of the Lower Miocene were divided into two groups, the larger browsers (*Oxydactylus*, Fig. 507 *B*) and the smaller grazers (*Protomeryx*).

The feet in both groups were like those of antelope and deer. This is a most significant fact, because in both grazing and browsing camels of the Lower Miocene the stocks were already distinctly separated. Neither had yet attained to the type of foot-structure which both of them afterward independently acquired. This is a very instructive example of parallel evolution in closely related series. In the Middle Miocene the browsers (*Alticamelus*) had already developed foot-pads, had attained to great size, with extremely long necks, enabling them to feed on the higher foliage of trees, and were at the acme of their importance. They were restricted to North America and died out in the Pliocene.

The true camels arose in the Middle Miocene in a generalized stock of smaller grazing animals (*Protolabis* and *Miolabis*) that probably were without the foot-pads. In the Lower Pliocene the llamas and true camels were clearly differentiated from one another, and the feet were provided with pads. In general structure they were not unlike the living species. Although some forms were large, they all died out in North America during the later Pleistocene.

Evolution of the Horses

Origin. — The horse family (Equidæ, from *Equus caballus*, the living horse) appeared almost simultaneously in Europe and America in the "dawn horse" (*Eohippus*) early in the Eocene, but it was in North America that this group of animals passed through the greater part of their later development. In Europe the horses died out in the Eocene, and Asia was restocked from America by way of Siberia and Alaska early in Miocene time. Late in the Miocene the horses of North America spread into South America. In the American Pleistocene there were many species of *Equus*, but the immediate ancestor of our domestic horse was not among them, and the entire tribe vanished in the later part of this period. The living species originated in Europe or Asia and was introduced into this country by the Spaniards.

Distinguishing Characters. — The living horses, asses, zebras, and quaggas belong to the odd-toed hoofed mammals (Perissodactyla) and are characterized by the very long and slender feet, each composed of but a single functional toe, the third digit. The animals walk upon the very tips of the toes, the wrist being what horsemen call the "knee," and the heel, the "hock." As the third toe in each limb supports the horse, it is necessarily much larger than in animals in which the weight is distributed among several digits. There is, however, on each side of the functional digit a vestigial one, the second and fourth of the original five in the ancient ancestors (Fig. 508). The whole structure of the horse is preëminently adapted to swift running; they are admirable running machines, and every part of the skeleton has been modified and specialized to that end.

The living horses are grazers and have extremely long teeth, the

molars being excessively complex in the arrangement of the enamel ridges and the areas of dentine and cement (Fig. 505). The grazing horses continue back into the Tertiary, but before the Middle Miocene all were browsers.

Evolution. — There is no stock of mammals better known than that of the Equidæ, and they have become the classic example or "show animal" of evolution. In fact, the famous Yale University collection, assembled by Professor Marsh, did much to demonstrate the truth of Darwinism (study Fig. 508). Scott summarizes the long and marvelous development of the horse family as follows: (1) In size there was a somewhat fluctuating increase, leading by slow gradations from the diminutive horses of the Lower Eocene, about the size of a cat or fox-terrier, to the great animals of the Pleistocene, about 14 hands tall. (2) The molar teeth, originally low, cusped, and with roots, gradually changed from the browsing type to the very long, prismatic, complex, grazing teeth, and the lower jaws grew in depth to accommodate this elongation. (3) The face grew relatively longer and the eyes were progressively shifted farther back. (4) The short neck was greatly elongated and the individual vertebræ modified so as to give flexibility with no loss of strength. (5) The limbs grew relatively much longer, the bones of the fore-arm and lower leg were fused together, the one on the inner side (radius and tibia) enlarging to carry the entire weight, and the external one (ulna and fibula) becoming more or less atrophied. (6) The feet were much elongated and the median or third digit of each gradually enlarged until it carried the whole weight, at the same time modifying the shape of the hoof so as to fit it to be sole support of the body. The other toes gradually dwindled and became functionless, though often retained as splints. The first digit was first lost, then the fifth, then the second and fourth were reduced to dew-claws and finally to splints. Thus the pentadactyl horses of the Lower Eocene were transformed into the monodactyl species of the Pliocene and Pleistocene.

Geologic Succession. — The most ancient known member of the family Equidæ was the "dawn horse," which swarmed in the forests and glades of the Lower Eocene (Wasatch). They were graceful little creatures no larger than a cat or about 11 inches tall at the withers. They had on the front feet four functional digits and the vestige of another, while the hind feet had three toes and two tiny splints, the vestiges of the first and fifth digits. This evidence clearly indicates that *Eohippus* originated in ancestors with pentadactyl feet. The molars were cusped and short and of the browsing type; the neck was very short, the body long, with an arched back, the limbs and feet short, and the hind limbs much longer than the fore (Fig. 508).

The Oligocene horses were intermediate in development between those of the

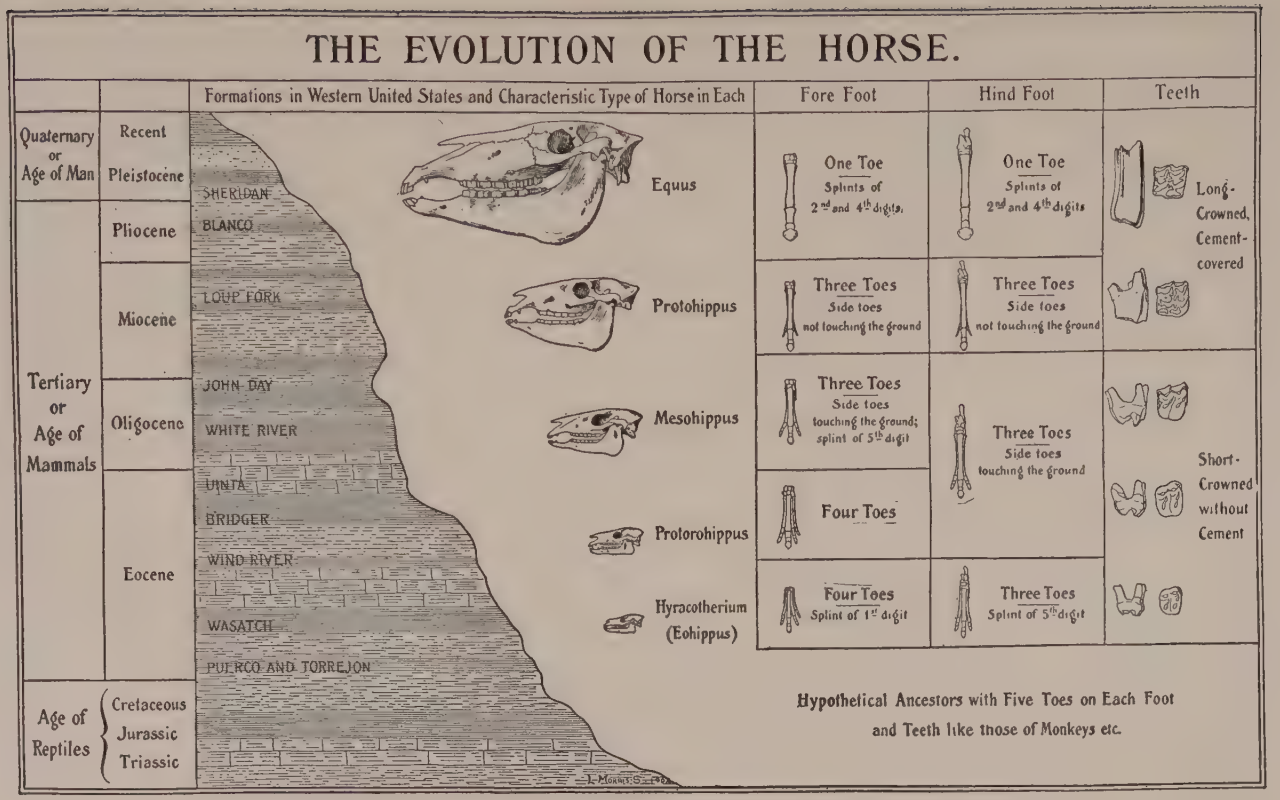


Fig. 508. — Diagram showing the evolution of the horse. After Osborn.

Eocene and Miocene. In the Lower Oligocene (White River) the largest ones were of the size of sheep (*Mesohippus*), and while the teeth were low-crowned and of the browsing type, they were changing toward those of the grazing animal. The front teeth had three functional toes, and even though the middle one was the largest, the two lateral digits touched the ground; the hind feet were also three-toed, but there were no splints present (Fig. 508).

In the Middle Miocene the three-toed horses were still mostly browsers, though some of the progressive ones were changing rapidly toward grazers. It is here that we get the intermediate forms (*Merychippus*) and note the splitting up of the horse family into several independently developing phyla. The Lower Pliocene had both progressive and conservative types of these animals. In the Middle Pliocene, among the herds of horses roaming the plains, there were three phyla of three-toed grazing horses, but the lateral digits no longer touched the ground; while they were "dew-claws," however, they were still at times of some supporting value. In the Upper Pliocene occurred the last of the three-toed browsing and grazing horses, and here lived also the first one-toed grazing member of the genus *Equus* (Fig. 508). In the earlier half of the Pleistocene there were at least ten species of the same genus, and among them horses larger than any now living.

Evolution of the Elephants

Origin. — The trunk-bearing mammals or Proboscidea had their origin early in the Tertiary of northern Africa. In the Fayum, southwest of Cairo, in late Eocene time lived the progenitor of the elephants (*Mœritherium*), an animal the size of a tapir. The head was long and narrow, with a rudimentary snout or proboscis, and the brain case was small. The most interesting feature, however, is the appearance of tusks that originated in the second incisors, the other front teeth remaining small. The incipient upper tusks were quite prominent and directed sharply downward, while those of the lower jaw were nearly procumbent, with a slight upward inclination (Fig. 509).

Evolution. — *Mœritherium* gave rise indirectly to *Palæomastodon*, an unmistakable proboscidian which persisted into the Lower Oligocene. It was about the size of a tapir, the narrow face was more drawn out than that of its ancestor, and there was a well-developed, flexible snout rather than a trunk. The tusks of the skull were longer, compressed, and more outwardly directed; those of the jaws, while larger, pointed straight forward. All of the grinding teeth (premolars $\frac{3}{2}$, molars $\frac{3}{3}$) were in place and functioned at the same time, which is not true of the later proboscidians (Fig. 509). The limbs were like those of elephants, but the brain was larger, and this tendency toward a greater cerebrum may have been the factor that permitted the proboscidians to flourish over most of the continents (Australia excepted), and to survive into the present time.

Africa and Europe were reunited at some time in the Oligocene, and across this land bridge the primitive elephants migrated into Europe.

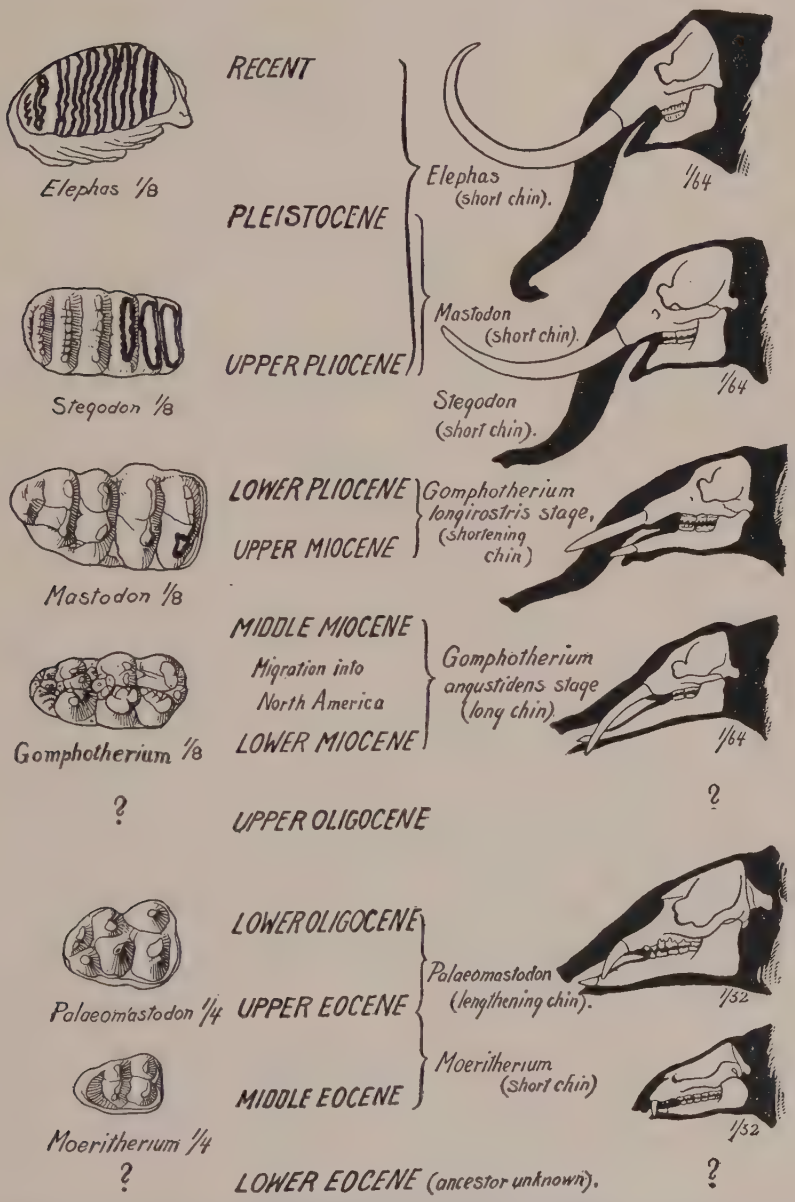


Fig. 509. — Evolution of the Proboscidea. On the right, a series of skulls with the flesh restored in silhouette. On the left, last lower molar. From Scott's *History of Land Mammals.*

They appeared suddenly in the Lower Miocene of France and by the Middle Miocene had spread into Asia and to North America. Finally, in Pliocene time, the mastodons, but not the elephants, reached South America.

It was the very long-faced, four-tusked proboscidians (*Gomphotherium*) that were so widely distributed in the Miocene and Pliocene (Fig. 509). These primitive forms gave rise in the Pliocene of India to the elephants and mastodons with two large tusks in the skull, while those of the jaws were absent or very rudimentary. In the Pleistocene of North America there were three kinds of elephants and one of mastodon (Fig. 513).

Summarizing the evolution of the Proboscidea, according to Lull: Increase in size and the development of pillar-like limbs to support the enormous weight; increase in size and complexity of the teeth and their consequent diminution in numbers and the development of the peculiar method of tooth succession; loss of the canines and of all of the incisor teeth except the second pair in the upper and lower jaws and the development of these as tusks; gradual elongation of the symphysis or union of the lower jaws to strengthen and support the lower tusks while digging, culminating in *Gomphotherium;* the apparently sudden shortening of this symphysis following the loss of the lower tusks and the compensating increase in size and the change in curvature of those of the upper jaw.

The increase in bulk and height, together with the shortening of the neck required by the increasing weight of the head with its great battery of tusks, necessitated the development of a prehensile upper lip which gradually evolved into a proboscis for food-gathering. The elongation of the lower jaw implies a similar elongation of this proboscis in order that the latter may reach beyond the tusks. The trunk did not, however, reach its greatest usefulness until the shortening jaw, removing the support from beneath, left it pendent as in the living elephant.

CHAPTER LIV

PLEISTOCENE TIME AND THE LAST GLACIAL CLIMATE

The Pleistocene or Quaternary, the final division of geologic chronology, and the culmination of the Cascadian Revolution, though brief as compared with the older divisions, was one of the critical times in the history of the earth. It was the time of the "Great Ice Age," and the record of the areas where the ice-fields prevailed consists in the main of a varied and most often a heterogeneous series of continental deposits, all of this being the Diluvium or deluge material of the older philosophers and the drift or tills of modern students of earth science. Outside of the areas of glaciation the strata are in general like other continental formations laid down under moist and warmer climates. The exposed marine record is nearly everywhere very scanty, and the molluscs are almost all (at least 90 per cent) or all still living. The life of the land was also dominantly of living forms, though here the percentage of extinct species was greater than in the seas. The term Pleistocene was therefore proposed by Lyell to bring out the fact that the life of this time was very much like that of the present.

Cold Climate of the Pleistocene. — The distinguishing physical feature of Pleistocene time was its very extensive glaciation; in fact, there appear to have been a series of glaciations, for ice-sheets covering about 8,000,000 square miles of the earth's surface existed at one time or another during this period in the temperate and colder regions of the two hemispheres (Fig. 510). This is all the more remarkable when we consider that the ice-sheets were mainly of the low lands, and that the climates for a very long time previous had been mild. All of the water of these ice-sheets had been taken from the oceans and precipitated as snow on the continents. The decrease of temperature was such that the snow-line (see page 111) was lowered about 4000 feet below its present limit (Fig. 512), and the strand-lines of the oceans in the tropical and warm temperate regions, because of the abstraction of ocean water, were depressed probably not less than 200 feet and not more than 300 feet. Finally, the loading of the lands with so much ice caused the crust to subside in the areas of the ice-sheets, while the regions immediately outside of the latter were

apparently somewhat upwarped in compensation by the displaced deep-seated material of the sinking fields. The surface of the glaciated lands was therefore more or less unsteady, warping up and down some hundreds of feet in consonance with the changes going on in the ice-sheets during Pleistocene time. In addition, broad crustal movements unrelated to the glaciation had been in progress during the Pliocene and continued at intervals in the Pleistocene. As a result of these combinations of several causes the streams and shorelines generally show at the present time the marks of extreme youth — sharp gorges, drowned channels, barrier beaches, and elevated strand-lines.

Critical Life Conditions during the Pleistocene. — The development of such immense ice-fields upon the lands and the attendant reduction of temperature also mean the blotting out of vast areas on which no life or at least but little could exist. The Pleistocene was, therefore, a critical time in the history of the earth, especially for the plant and animal life of the glaciated lands and the shallow-water life of the northern and southern oceans. The cold waters, pouring into the oceans, sank into the depths, and the conditions there also became critical for the sparse life. In the shallow waters of the warm parts of the ocean, however, there was almost no change in the environment, and consequently there is recorded here almost nothing more than the usual evolutional faunal alterations.

Recent Time. — The Pleistocene was followed by the Recent, or present time, but how long this has been going on can not yet be stated. In a general way, we may say that the estimates vary between 20,000 and 50,000 years, with the probability that the smaller figure may be nearer the truth. As man has dominated the organic world since the beginning of the Recent, this is also known as Psychozoic time, a name given it by Le Conte. We are living in the opening events of a new era, the Psychozoic Era, but how long it is to last before another critical closing time appears, who can tell?

General Distribution of Glaciation

In the discussion of Pleistocene glaciation it should be recognized that the ice has only partly withdrawn. Greenland and Antarctica are still mantled with continental ice-sheets in contrast to their unglaciated state in earlier periods. It is the excess of glaciation beyond the present areas that is to be considered in the discussion of the wide distribution of the ice-fields of the Pleistocene.

More than half of the glaciated area during the Pleistocene was in North America, and more than half of the remainder in Europe.

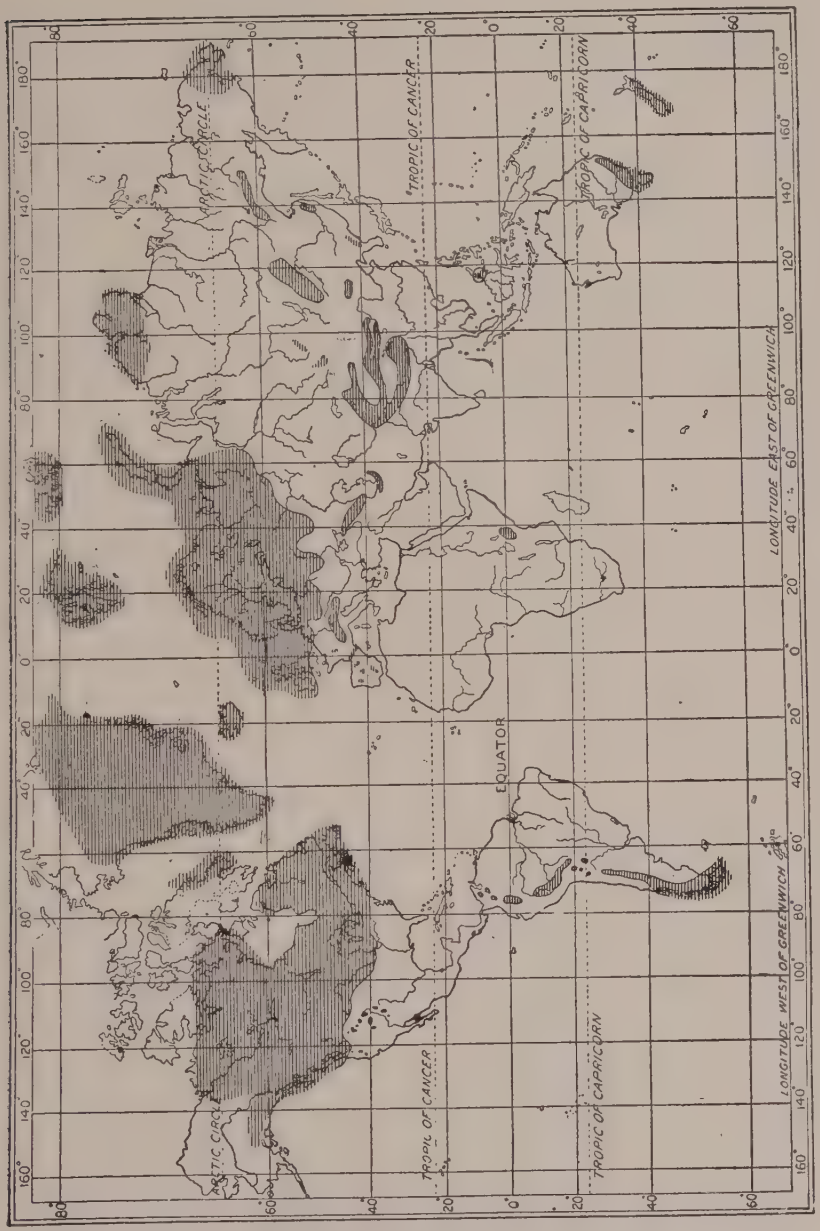


Fig. 510. — World map of Pleistocene glaciation. Carnegie Institution of Washington.

The glaciation was, therefore, notably localized, though its effects were world-wide (Fig. 510).

North America. — In North America it was mainly the north-eastern half, and the plains country rather than the mountainous region that was deeply buried under the continental glaciers (page 118). Alaska was in the main free of ice and the same appears to have been true of the Arctic archipelago. There were three great centers of ice accumulation and radiation in North America, covering together an area of about 4,000,000 square miles (Fig. 511). The

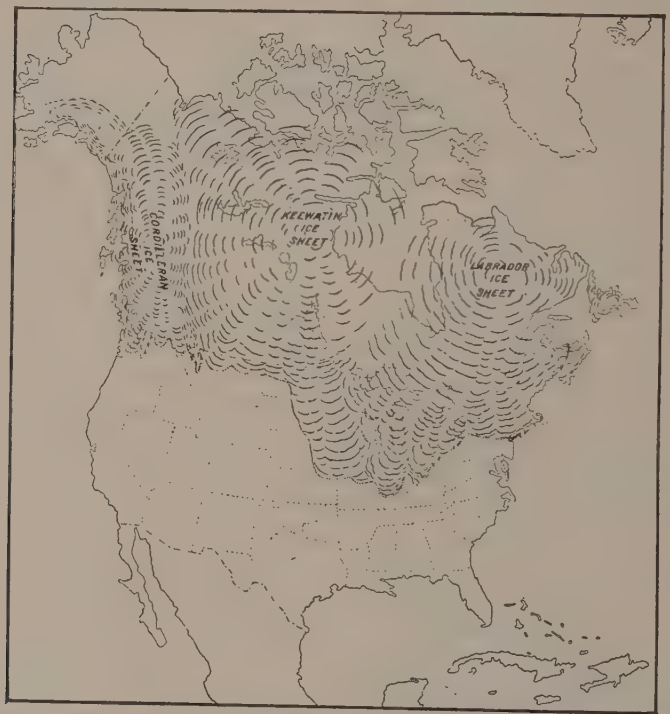


Fig. 511. — Map of maximum glaciation of North America. After Salisbury.

Keewatin ice-sheet was the most extensive, covering the great medial flat area of the continent southward into Missouri and westward into the high plains to within 800 to 1000 miles of the Rocky Mountains. The *Labradorean ice-sheet* was not much smaller, and extended from northern Labrador southwestward for 1600 miles to the Ohio River. The main flow of the ice was southward toward the region of melting, marked by greater warmth. *Newfoundland* and *Nova Scotia* appear to have had independent ice-sheets, while *Greenland* was glaciated more extensively than now but not completely across Davis Strait so

as to connect with the Labradorean mass. The *Cordilleran ice-sheet* covered all of the Cordilleran area from Alaska southward into Oregon, Idaho, and Montana. Farther south there were local alpine glaciers in the Rocky Mountains and in the Coast Range and the Sierra Nevadas of California.

Other Countries. — All *northwestern Europe*, *Iceland*, and *Spitzbergen* were deeply buried under ice-sheets, and the glaciers of the Alps descended far beyond their present limits and coalesced on the low lands in all directions. In the Himalayan region and locally in eastern Asia there were other mountains which were broadly glaciated. In the southern hemisphere, doubtless because of the absence of broad lands in high latitudes, there was comparatively little glaciation, most of it being restricted to the Andean areas. *Antarctica* is assumed to have been as deeply covered with ice then as it is now. (See Fig. 510.)

Thickness of the Ice-sheets. — How thick the Keewatin and Labradorean ice-sheets were is not known. It is widely held, however, that they must have been some thousands of feet in depth to have enabled them to flow southward with a descending grade across the higher irregularities. Le Conte places the thickness at 10,000 feet over Canada and 6000 feet over New England, where the depth is known to have been at least 4000 feet. Geologists as a rule believe that the thickness at the centers of ice dispersion could not have been less than 4000 feet, and that it may have exceeded this average depth.

Alternating Cold and Warm Stages

It is a well-known fact that in most areas of past glaciation there occur, between sheets of drift, beds of peat and clays with fossil leaves and wood, and sands with bones of many kinds of large mammals. These fossils show clearly alternating groups of plants and animals living in different climates; one set is of northern origin and of cold habitat, while the following one is from the south and of mild climes. The cold climate assemblages have among other forms reindeer, caribou, musk-oxen, moose, woolly mammoths (Fig. 513 *C*), and walrus, while those of the warm climates have lions, sabre-tooth tigers, peccaries, tapirs, camels, llamas, many horses, hippopotamuses, great sloths (Fig. 514), the Columbian and Imperial elephants (Fig. 513 *B*, *D*), and the manatee or sea-cows. It is the succession of these fossils in the Pleistocene strata that has led to the discerning of alternating warm and cold climates. These marked alterations led to very extensive migrations of mammals from one part of the continent to another, as the conditions of temperature and moisture changed. During the warm interglacial times, southern species

spread far to the north, as when mastodon ranged into Alaska (Fig. 513 *A*) and the sea-cow spread north to New Jersey. Increasing cold and the spread of glaciation brought about a reverse migration and drove northern and even Arctic forms far to the south. Musk-oxen then spread into Utah and as far south as Oklahoma, the northern or woolly mammoth (Fig. 513 *C*) lived south of the Ohio and Potomac rivers, and the walrus had its home along the strands of New Jersey.

It has come to be generally held, therefore, that during the Pleistocene the temperature varied more than once between cold and warmer climates. During the cold times there was increase in the extent and thickness of the continental ice-sheets, and during the warmer interglacial stages the ice was melted away to a greater or less

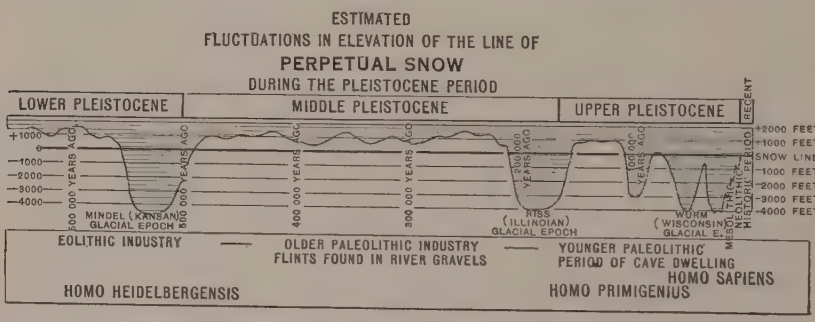


Fig. 512. — Diagram illustrating the probable variations of the snow-line during most of the Pleistocene and Recent, on the basis of a conservative time estimate stated in years. Drawn to scale. The succession of human events is also indicated. Prepared by Joseph Barrell.

degree. However, as to the number of these alternations there is as yet no unanimity among geologists, because of the great difficulties in correlating the separated areas of glacial material, all of which are so much alike. Some geologists recognize three, and others as many as six glacial stages, with from two to five interglacial warmer times (Fig. 512).

It is also now widely accepted that the interglacial times were markedly variable in duration and that all of them were not only warmer than the present, but that they lasted longer, and sometimes much longer, than the glacial stages. In Europe one of the interglacial times was so warm that the lion and the hippopotamus lived in England, and in North America the pawpaw bush spread north at least as far as Toronto while to-day it is not known to live much above the Ohio River.

Chamberlin and Salisbury divide Pleistocene time as in the first column of the following table, and the statements concerning the mammals in the second column are after O. P. Hay.

Divisions of Pleistocene time in North America

Post-glacial or present time	Vanishing of ice-sheets. Champlain marine invasion. Lowering of water-level of Great Lakes. Gradual amelioration of climate. Gradual extinction of elephants, mastodons, *Megalonyx*, musk-oxen, etc.
Fifth or Wisconsin glacial stage Würm stage in Europe	Spread of ice-sheets and drift. Fauna and flora driven south.
Fourth or Peorian interglacial stage	Record not well determined. Formation of peat beds and soils. Wide distribution of loess.
Fourth or Iowan glacial stage	Spread of ice-sheets and drift. Record not well determined.
Third or Sangamon interglacial stage	Accumulation of peats, soils, and loess. Horses, elephants, mastodons, bison, peccaries, and tapirs probably present.
Third or Illinoian glacial stage Riss stage in Europe	Spread of ice-sheets and drift. Deposition of loess. Apparently 60 per cent of present land fauna then living. Mastodons, mammoths, horses, tapirs, bison, deer, and sabre-tooth tigers.
Second or Yarmouth interglacial stage	Formation of peats, soils, and bluish loess. Animals about as in Illinoian stage.
Second or Kansan glacial stage Mindel stage in Europe	Spread of ice-sheets and drift. Extinction of certain camels and horses.
First or Aftonian interglacial stage	Great abundance of mylodons, megatheres, *Megalonyx*, mastodons, elephants (3 species), horses (6 species), camels (4 species), sabre-tooth tigers, bears, etc. A warm temperate fauna.
First or Sub-Aftonian glacial stage	Spread of ice-sheets and drift. Includes Pre-Kansan, Nebraskan, and Albertan drifts.
Pliocene	

Effects of the Glacial Climate

Historical. — During the greater part of the past century, geologists holding strictly to supposed implications of the Laplacian theory of earth origin believed that the earth had been gradually cooling and that it became cold for the first time in the Pleistocene. When, therefore, the first announcements were made, nearly fifty years ago, that a cold climate had been present in the Permian (see

page 758) most of our colleagues of those days could not accept what is now undoubted evidence. The controversy over the origin of the Pleistocene glacial deposits, however, not only made it possible to accept the evidence of the drifts and tills as the result of ice work, but paved the way for the evidence of other and older geologic climates. We now know that such occurred much farther back in the history of the earth, one toward the close of, and another earlier in, Proterozoic time (pages 570 and 560). There is evidence of yet other cool periods, and it is probable that we shall learn that the earth has undergone more than four glacial climates (see Fig. 520).

Our knowledge of glaciation had its origin in the Alps, the land of magnificent scenery and marvelous glaciers, through the work of Andreas Scheuzer early in the eighteenth century. This was at first only a study of the interesting local glaciers, but out of it gradually came about, especially through the studies of Louis Agassiz between 1836 and 1847, the application of conditions observed in the Alps to the very widely distributed glacial deposits elsewhere. (The characters of glaciers are described on pages 111 to 119.) The engineer Venetz in 1821 pointed out that the Alpine glaciers had once been of far greater size, and that glaciation had been on a scale of enormous magnitude in some former period. By degrees the older conception that the erratics and tills were the result of marine floodings and floating icebergs gave way, in the third quarter of the last century, to the theory of colder climates and glaciers of continental extent. (For a detailed description of glacial deposits see pages 134 to 140.)

Changes in Drainage due to Ice-sheets. — The geologic work done by glaciers in general is described on pages 128 to 134. Erosion by the continental ice-sheets was unequal and the deposition of the drift materials was especially irregular in distribution. From this it follows that the drainage system of the land was deranged and considerably modified. River valleys were locally filled by the drift to depths ranging up to 400 feet, or partially covered over by the ice, forcing the drainage around its front, as was the case in the middle course of the Ohio River. In fact, the drainage of the glaciated areas was in certain regions revolutionized. Chamberlin and Salisbury state that there were few streams of great length in the areas covered by the ice that were not turned from their old courses for greater or less distances by the ice or the drift. The Ohio and the Missouri — the master streams of the United States marginal to the glaciated area — were built up from previous systems, and a host of their tributaries within the glaciated area suffered marked changes.

Origin of the Great Lakes. — All ice-sheets push out lobes along the preëxisting valleys, and those of the Great Ice Age, especially during the Wisconsin stage, were no exception to this rule. Accordingly, the Keewatin ice-sheet, when it finally melted and re-

treated across the area of the Great Lakes, had lobes that extended along the ancient valleys (see Fig. 104), scouring them deeper, and leaving in front, as they receded, small lakes that grew to ever greater proportions and were variable in outline. The first to appear were Lake Chicago, the beginning of Lake Michigan; Lake Saginaw, a part of the future Lake Huron; and Lake Whittlesey, which was of considerably larger extent than its descendant, Lake Erie. At this time, certain of the present small rivers were large, as the St. Croix, Wisconsin, Rock, and Illinois, draining the vast melting waters of the Keewatin ice-field into the Mississippi River. In central New York the "finger lakes" were considerably larger than they are now and their waters for a long time drained into the Susquehanna River, and later through the Mohawk and Hudson rivers. Finally, when the ice had retreated well into Canada, all the Great Lakes were connected far more widely than they are now and drained out eastward through the Ottawa and St. Lawrence into the Champlain marine inundation, to be explained later.

Lake Agassiz. — As the ice retreated from Minnesota, the Dakotas, and Manitoba, it left a shallow basin in which another great lake came into existence. Lake Agassiz, as it is called, was once five times as large as Lake Superior, but when the ice-sheet which blocked its northern edge finally melted away, the waters of the lake were drained off, leaving only much smaller lakes, such as Winnipeg, in the deepest parts of its basin. Its existence has been determined from the many raised terraces and sandy beaches made by its waves, and by the broad, flat bottom built of fine silts which were deposited in the lake. This alluvial plain is now one of the richest wheat-growing districts in the world. For other large lakes of Pleistocene time, such as Lakes Lahontan of Nevada and Bonneville of Utah, see pages 79 and 80.

Champlain Marine Invasion. — When the ice-sheets had finally retreated into Canada and across the St. Lawrence valley, the Atlantic Ocean found the glaciated lands depressed, and not only entered the depression but filled it at least 600 feet deeper than now. This was, therefore, a time of inland or epeiric seas, and it is probable that at this time also appeared Hudson Bay. In other words, a great part of eastern North America sunk under the enormous load of the ice-sheet and when the latter vanished the Atlantic was permitted to flood deeply Hudson Bay, the St. Lawrence and Ottawa valleys, all of Lake Ontario and Lake Champlain, and southward to the east of Lake George. Marine shells and the bones of whales and seals are found about Lake Champlain at elevations of up to 440 feet above

the present level of the water, and at 520 feet near Montreal (see page 73 under relic lakes and page 493).

Oscillations of Strand-lines. — At no time in the Pleistocene earlier than the Champlain invasion is it known that either the Atlantic or Pacific oceans to any great extent invaded the continent. In other words, North America stood higher above the strand-line than was the case at any time during the Tertiary. However, it is known that the strand-line was not constant, but that it oscillated up and down within some hundreds of feet. These alternations were probably due to the warping up and down of the continent, as explained on an earlier page.

Marked Changes in Europe. — During the Pleistocene Great Britain remained in connection with northern France (region between Calais and Boulogne) and the then eroding outer valleys of the Seine and Somme are now flooded by the English Channel. On the other hand, the Thames and the great Pleistocene Rhine flowed out much farther north, and their outer plains and valleys are now occupied by the North Sea. The shallow Baltic Sea, like Hudson Bay, also originated in Pleistocene time. In southern Europe great down-sinking of certain basins has been in progress, and the Black Sea of southeastern Europe is of very recent origin. Sicily and Malta were united to Africa and the connecting land was faulted into the depths of the Mediterranean at about the Middle Pleistocene.

Duration of the Glacial Period.— There is as yet no definite method of determining the length of time that the Pleistocene endured. The estimates are matters of judgment and therefore little more than guesses. It is assumed that the Pleistocene came to a close about 20,000 to 50,000 years ago. All of Pleistocene time has been estimated at not less than 400,000 years, and some geologists suggest that it may have endured even longer than 1,400,000 years. The truth probably lies somewhere between these estimates, with the probability toward the smaller figure (see Fig. 512).

Record of Lands to the South of the Ice-sheets

The glaciated area has a topographic expression all its own, for here we find the drift in its many forms, erratic stones, large and small, and a striated and scoured ground. Soils are mostly yellowish and thin or absent, and everywhere occur lakes of varying sizes occupying the depressions. In front of the ice-sheets occur the deep old soils that are usually of a reddish color, there is no drift, erratics or striated ground, the lakes and ponds are comparatively few and due to other causes. The streams are flowing in their old courses, but at lower levels.

The stratigraphic record of the warmer areas of Pleistocene time is scattering, varied, and fragmentary, and it is therefore difficult to

determine the chronologic sequence. There are wind deposits of sand and dust along the rivers and the shores of lakes, and in various arid areas occur accumulations of dust; elsewhere there are sediments of rivers and lakes and the deposits made by springs, asphalt pools and fillings of caves and sink-holes often abounding in bones, peats and marls of marshes and ponds, lavas and ashes in the areas to the west of the Rocky Mountains, and finally the fresh-water, estuarine, and marine accumulations along the borders of the continent. All of these deposits are apt to be thin and localized.

Causes of Glacial Climate

As yet there is no accepted explanation of why the earth from time to time undergoes glacial climates, but it is becoming clearer that they are due rather to a combination of causes than to a single cause. Probably the greatest single factor is high altitude of the continents, with great chains of new mountains (the hypsometric causes) which disturb the general direction and constitution of the air currents (the atmospheric causes) and the ocean currents as well.

Hypothesis of Polar Wandering. — It has often been suggested that the axis of the earth has shifted and that the north pole in Pleistocene time was 15° or 20° south of its present position. To explain the equatorial glaciation of Permian time some writers have shifted the north pole to the region of Mexico, and the south pole to the Indian Ocean; even if this were possible, however, the distribution of the ice-fields did not center about these imaginary poles. As the earth is essentially as rigid as steel, the dynamic conditions in such a mass would not permit of such changes without leaving a record of them in the structure of the earth-shell. There are no such records discernible. Moreover, it was long ago demonstrated mathematically by G. H. Darwin that migrations of the axis of the earth sufficiently extensive to be of geological importance have not occurred. "It would appear," says Barrell, "that the assumption of polar wandering as a cause of climatic change and organic migration is as gratuitous as an assumption of a changing earth orbit in defiance of the laws of celestial mechanics."

Effects of Continental Emergence. — Of the four known glacial climates of geologic history, at least three (early Proterozoic, Permian, Pleistocene) occurred during or directly after times of intensive mountain making, while the fourth (late Proterozoic) apparently also followed a time of elevation. The Laramide Revolution at the close of the Mesozoic, on the other hand, was not accompanied by a glacial climate, but only by a slightly cooler one. The cooled Lias time (page 851) also followed a mountain-making period. We therefore see that the known cooled or cold climates occurred during or immediately followed periods of marked mountain making.

Again, the three marked glacial climates of late Proterozoic, Per-

mian, and Pleistocene times and the cooled climates of the Lias and Cretaceous all fall in with times when the continents were more or less highly emergent. There were no cold climates when the continents were flooded by the oceans, and it may be added that the periods of wide-spread limestone making preceded and followed, but did not accompany, the reduced climates (see Fig. 520).

Effect of Volcanic Ash in Atmosphere. — Humphreys has shown that volcanic dust, shot very high above the cloud region of the earth's atmosphere, where it may continue to float for months, does appreciably reduce the temperature at the surface of the globe. The greatest amount of dust in the atmosphere should, therefore, coincide with the times when the volcanoes are most active, or when mountains are being elevated. An analysis of the climates during these times shows that while they may have been cooled, the dust in the higher atmosphere of the earth does not appear to have been a primary factor in bringing on glacial periods. On the other hand, it can not be denied that such periodically formed blankets against the sun's radiation may have been a contributory cause in cooling climates during some of the periods when the continents were highly emergent.

Effects of Oceanic Spreading. — The life of the seas of the past indicates vast stretches of time of mild to warm and equable temperatures, with but slight zonal differences between the equator and the poles. These were punctuated by short but decisive periods of cooled waters and great mortality, followed by quick evolution and the rise of new stocks. On the land the story of the climatic changes is different, but in general the equability of the temperature simulated that of the oceanic areas. The lands were, however, periodically inundated by warm waters, causing insular climates that were milder and moister. With the vanishing of the floods, somewhat cooler and certainly drier climates were produced. (See Figs. 520 and 521.)

When to these factors is added the effect upon the climate of the periodic rising of mountain chains, it is apparent that the lands must have had constantly varying climates. In general, the temperature fluctuations seem to have been slight, but geographically the climates varied between mild to warm pluvial and mild to cool arid. Finally, it must not be forgotten that when the lands were highly emergent, the formerly isolated lands were connected by land bridges that more or less altered the oceanic water circulation and therefore the local temperature.

Effect of Carbon Dioxide in Atmosphere. — A great deal has been written about the supply and consumption of the carbonic acid of the air as the primary cause for the storage of warmth by the atmospheric

blanket. A greater supply of carbon dioxide is said to cause increase of temperature, and a marked subtraction of it to bring on a glacial climate (see pages 84 and 457). This aspect of the climatic problem is altogether too large and important to be entered upon here. It is permissible to state, however, that the glacial climates are irregular in their geologic appearance, are variable latitudinally, as is seen in the geographic distribution of the tillites between the poles and the equatorial region, and finally that they appear in geologic time as if suddenly introduced. These differences do not seem to be conditioned in the main by a greater or smaller amount of carbon dioxide in the atmosphere, for if this gas is so strong a controlling factor, it would seem that at least the glacial climates should not be of such quick development. On the other hand, an enormous amount of carbon dioxide was consumed in the vast limestones and coals of the Cretaceous, with no glacial climate as a result; though it must be admitted that the great limestone and vaster coal accumulations of the Pennsylvanian were followed by the Permian glaciation. Again, it may be stated that the Pleistocene cold period was preceded in the Miocene and Pliocene by far smaller areas of known accumulations of limestone and coal than during either the Pennsylvanian or Cretaceous, and yet a severe glacial climate followed.

Effect of Variation in Solar Energy. — As all of the appreciable heat of the atmosphere is derived from the sun, it is necessary to examine this source to see if the quantity varies. It is now well known through the work of Langley and Abbott that the sun is a slightly variable star and that the output of radiation is variable within limits of from 5 to 10 per cent in quantity and in irregular periods of from five to ten days. Moreover, Huntington states that five authorities on glaciation have concluded that if the mean temperature of the earth were to fall 9° or 11° F. and were to remain thus low for a sufficient length of time, meteorological conditions would be so altered that a large part of North America would be covered with ice down to about the fortieth degree of latitude, and Europe would suffer a corresponding glaciation. Of course there is no direct evidence to show that the intensity of solar radiations has varied so greatly in past times. That it does vary in a minor degree, however, has been shown. This being so, Huntington postulates that at certain times the sun may have been stimulated to unusual activity, just as it is to-day when we have periods of unusually numerous sun-spots, but to a greater degree. During the times of great but short stimulation, the sun's atmosphere would also be laden with much dust, shutting in the solar heat and cooling the thermal blanket of the

earth to the extent of bringing on a glacial climate. As the solar atmosphere became clearer and more and more of its heat radiated into space, the earth would become warmer, giving rise to a long interglacial stage of usual warmth or aridity. Finally it should be added that as cold climates appear during or shortly after excessive mountain making on the earth, crustal unrest and reduced climates occur simultaneously with the hypothetical stimulations of the sun. (For further detail concerning this theory see Huntington, *The Climatic Factor*.)

Conclusions. — Briefly, then, we may conclude that the markedly varying climates of the past seem to have been due primarily to periodic changes in the sun and in the topographic form of the earth's surface, plus variations in the amount of heat stored by the oceans. The transformed face of the earth altered the configuration of the continents and oceans, the air currents (moist or dry), the oceanic currents (warm, mild, or cool), and the volcanic ash content of the atmosphere. The causation for the warmer interglacial climates may lie in the oscillations of solar energy.

Life of the Pleistocene

The most interesting life of the Pleistocene is naturally the mammalian, and even though it is as a rule very fragmentary, it is so widely scattered as to give a fair idea of its extent. In fact, as Scott says, with all its gaps, the record is impressive. The human history will be presented in the next chapter.

The most striking of the Pleistocene mammals in North America were the three species of elephants and the one of mastodon. The last named, *Mammut americanum*, migrated from Siberia into Alaska, and ranged over nearly all of the United States and southern Canada (Fig. 513 *A*). It was most abundant in the forested regions and rarer in the plains country, and persisted so long that the animal may have been hunted to extermination by the red men.

Of the elephants, the most interesting and widely distributed was the Siberian woolly mammoth (*Elephas primigenius*), an animal of the cold climate, standing about 9 feet tall at the shoulders, and coming to North America by way of Alaska (Fig. 513 *C*). It ranged from the far north through British Columbia into the United States and across to the Atlantic Coast. The mammoth also migrated from Asia into Europe and was there hunted by Pleistocene man (see Fig. 519). It died out in North America late in Pleistocene time.

Closely related to the above form was the Columbian elephant (*Elephas columbi*), of taller stature, being 11 feet at the shoulders

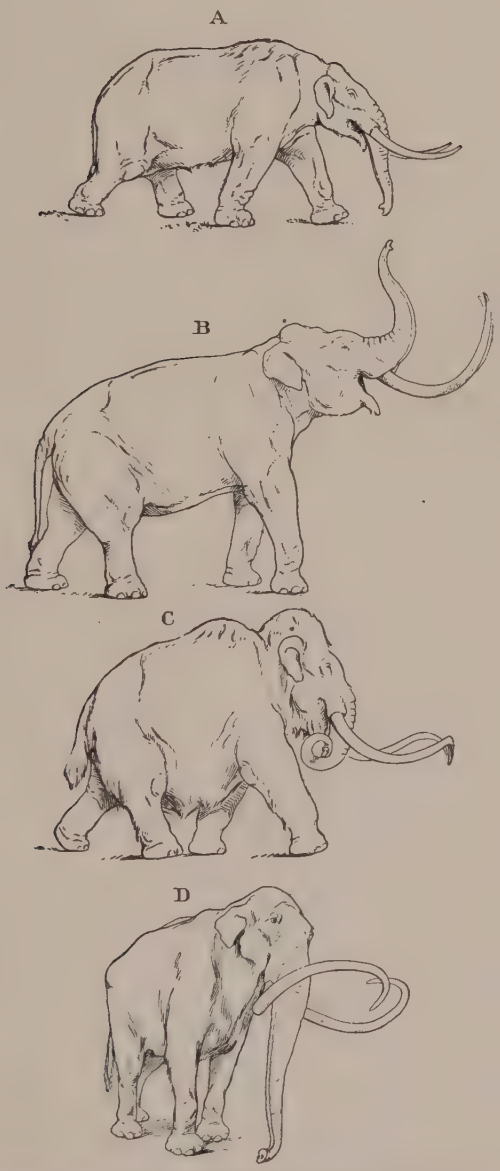


Fig. 513. — Restorations of the American Pleistocene proboscidians. *A*, American mastodon (*Mammut americanum*). *B*, Imperial mammoth (*Elephas imperator*). *C*, woolly mammoth (*E. primigenius*). After Osborn. *D*, Columbian mammoth (*E. columbi*). From Scott's *History of Land Mammals*.

(Fig. 513 *D*). It lived during the earlier half of Pleistocene time in the warmer portions of North America, roaming over the whole United States and the high plains of Mexico. The third species was the huge Imperial elephant (*Elephas imperator*), said to attain to 13 feet and 6 inches in height (Fig. 513 *B*). It was probably a plains animal that survived from Pliocene times and died out in the Middle Pleistocene. Its range was western America from Nebraska to Mexico City.

The horses were exceedingly numerous in the earlier Pleistocene, and roamed, apparently in great herds, all over Mexico and the United States and even into Alaska. There were at least ten species of *Equus*, one no larger than the smallest pony, others larger than the heaviest modern draft-horses. They were descendants of American Pliocene horses and all died out during the Pleistocene.

Of peccaries there was an abundance, and there were also camels and llamas. During the times of glaciation the caribou ranged south into Pennsylvania and musk-oxen into Utah and Oklahoma. The modern moose was present in the western half of the continent, but the stag-moose (*Cervalces scotti*) was a late arrival during the last ice invasion. Other ruminants related to the musk-ox occurred earlier in the period, and of bison there were at least seven kinds, ranging from Florida to Alaska, one species (*Bison latifrons*) with a horn spread of 6 feet.

Among the carnivores, the most formidable was the great sabre-tooth tiger (*Smilodon*), which lived over the greater part of the United States. Of rodents the most interesting was the late Pleistocene giant beaver (*Castoroides ohioensis*), as large as a black bear.

The ground-sloths were represented by a large and widely spread form, *Megalonyx*, first discovered and named by President Thomas Jefferson. The giant southern form, *Megatherium* (Fig. 514), had a body as large as that of an elephant, though shorter in limb, while the oldest and smallest of the sloths was *Mylodon*.

Fig. 514. — Giant sloth (*Megatherium*) and two kinds of glyptodonts (*Glyptodon* above, *Dædicurus* below), from the Pleistocene (Pampean) of Argentina. After J. Smit, from Knipe's *Nebula to Man*.

CHAPTER LV

MAN'S PLACE IN NATURE

The title of this chapter is the same as that of one of Huxley's famous books, in which he states: "The question of questions for mankind — the problem which underlies all others, and is more deeply interesting than any other — is the ascertainment of the place which Man occupies in nature and of his relations to the universe of things."

Man Compared with Animals.* — Man seems to us so very different from all the animals that we can not believe him to be related to them at all, and prefer to regard him as standing isolated and alone, something quite apart from all organisms. When, however, we begin to study his body and compare it, organ by organ, with that of other animals, we see that his isolation disappears, and that it is the thick veil of civilization in which he has so completely hidden himself that misleads us regarding his true position in the animal kingdom.

Stature and Posture. — The mean stature of present-day Europeans is 5 feet 6 inches, and we shall see later on that the oldest fossil men vary between this size and 5 feet 4 inches. Men of 6 feet in height did not appear until toward the close of the Glacial Period (Pleistocene) in the Aurignacian race of France. We are, therefore, not descended from a race of giants, but rather are we tending toward a taller stature.

The erect posture of man is also of ancient origin, for it is fully developed in the oldest fossil men, and probably had its beginning in the gibbons of Pliocene time. It is, however, not so much in his posture that man differs from the large anthropoids as in his manner of progression. He is adapted to living on the ground, "an adaptation which allowed him to escape beyond the limits of forests and occupy the whole world." It is, therefore, in the construction of the legs and in the setting of the entire foot upon the ground (plantigrady) that man varies much from the greater apes, and as the human leg and foot are already developed in the oldest known fossil man, it is

* Most of the information in the first half of this chapter has been taken from Keith's *Man, a History of the Human Body.*

clear that this evolution also took place prior to the Pleistocene. It was during this earlier evolution of man that the great toe, set like a thumb and used as a grasping organ, was changed into the non-grasping toe of living man. The human type of leg and foot was, then, developed long before the human brain came to be as we see it now, for in the oldest fossil ape-man (*Pithecanthropus*) the brain is little more than half the size of that in living man. The large brain of man appears to be his latest acquisition; his foot, leg, and plantigrade gait are older, his size of body older still, and his erect posture quite an ancient character.

Comparisons between Man and the Other Primates. — "The skeleton of the gorilla is not at all human in appearance, the great crests on the skull, the massive jaws and face, the long stout arms, the short lower limbs with a thumb-like great toe, seem to assure us that even the most man-like of apes is a long way off from man himself. Yet when we look more closely we see that every bone of man's body is present in the gorilla, they occupy exactly the same place in the skeleton; each bone shows the same leading features; the differences relate merely to proportion, size, and detail. When we look at the skull of the young gorilla, before the massive, brute-like crests have appeared, the human resemblance is more marked. In the skulls of the adult chimpanzee, these cranial ridges, which are developed to give attachment to the great muscles of mastication, are much smaller than in the gorilla. In the orang they are intermediate in size."

Between the higher apes just mentioned, which Huxley refers to as "blurred copies" of man, and the smaller and lower apes, the gibbons, there is another break in the evolutionary steps quite as marked as the one between man and the great anthropoids. The head and body are much smaller, there are the same bones set together in the same order, but the proportions are different. The gibbons are of early geologic origin and have clung to the ancestral form more closely than any of the other apes. Between the gibbons and the monkeys there is a wider gulf than any we have so far seen, yet we can not well say the one is higher than the other. In certain features we see that the gibbons are related to the Old World monkeys, in others to those of the New World; we believe that there must be extinct ancestral gibbons which, did we know them, would show us that these three forms of primates have all arisen from a common stock at a long past period of the world's history. Among the American monkeys we find quite small and low forms, such as the marmoset, which take us a little way toward the lemurs. "If at first

we had seen the skeleton of man placed side by side with that of the tiny marmoset we would have denied that there could be any possibility of a common origin for these two, but when we pass from the one to the other through a series which, while showing many breaks, leads us step by step from the one to the other, we begin to see that the miracle of man's primate origin is not so impossible as it appears at first."

Geologic Rise of Primates. — The oldest lemurs appear in the American Eocene (Wasatch) in a small form very much like the tarsier living in Madagascar. Diminutive monkeys appear a little later (Bridger), but before the close of the Eocene all primates seem to have become extinct in North America. In the later Oligocene of Egypt appears the oldest ape (*Propliopithecus*), apparently the progenitor of all later anthropoids. This was a small animal which spread in early Miocene time into Europe and there gave rise to the larger apes of the western part of that continent (*Pliopithecus* into *Dryopithecus*). It is, then, since Middle Miocene time that we may expect the rise of the human stock. The great-bodied primates of about this time probably divided into two independently evolving stocks, the one retaining the ancestral arboreal habitat, the other taking more and more to the ground. The former line of evolution gave rise to the gorilla and chimpanzee of Africa and the orang of Borneo and Sumatra, while the terrestrial stock developed into the ancestry of man. Living man is known as *Homo sapiens* (reasoning man) and in his varied geographical races is distributed over the entire earth. As we go back into the Pleistocene we meet with other human species, more and more primitive, and finally with the ape-man (*Pithecanthropus*) of Java.

Brain in Primates. — The brain of the higher vertebrates consists of two main parts, a lower and hinder division known as the cerebellum, and an upper part, the cerebrum, that is again divided into right and left hemispheres. In the mammals previous to the Oligocene the lower brain is the larger, but beginning with this time the upper brain, where reason and memory are located, increases rapidly in size in nearly all stocks and finally is considerably greater than and almost covers over the entire cerebellum.

In man the size of the brain depends to a certain extent upon the bulk of the body; tall men on the average have larger brains than small men. It therefore does not hold true that bulkier men with larger brains are more able than smaller ones with less weighty brains, though the fact remains that many of the world's most famous men had large heads and big brains. The brain of Bismarck and Cuvier

each weighed about 66 ounces, that of the Russian novelist Turgenieff nearly 75 ounces, while that of Gambetta, the French statesman, weighed about 42 ounces, and that of Leibnitz, a great German philosopher and mathematician, less than 45 ounces. In adult men the weight of the brain varies between 65 and 34 ounces (average 49), and in women, due to their smaller size, it is between 56 and 31 ounces (average 44) or about 12 per cent lighter than in man. When the brain is contrasted with the entire weight of the body it is about as 1 to 45.

In the smallest gorilla the brain weighs 15 ounces and in the largest 20 ounces, while the weight of the entire body at maturity varies between 200 and 418 pounds, giving a ratio of about 1 to 213. At birth the human brain weighs between 10 and 11 ounces, or about one fifth its size at maturity. By the end of the second year the human brain has attained two thirds of its adult size, and has then reached the same relative degree of development that the anthropoid has at birth. Maximum size of the brain in man is reached at about the twentieth year, and it then slowly loses weight into old age, when decrease is more rapid. "Man's prime is not a period," says Karl Pearson, "it is merely a point of time."

Embryology of Man. — All animals, however simple or complex in construction, begin in a single cell with a nucleus, and the human species begins in the same way. Thus all the higher organisms begin in comparative simplicity and develop through growth into greater complexity. The human ovum or egg, considered as a cell, is large, but actually is so small that about 125 of them when laid side by side have a length of one inch only; while the male or sperm cell that enters the ovum and starts its development is vastly smaller. Therefore, the tiny microcosm of living female and male matter has within itself the potentialities of the future man or woman, and the individual during its development and mature existence reveals not only the characters of its direct human ancestors but something of its animal line of succession as well. It is during the first three months of fœtal development that all of the great changes or transformations take place and that all parts of the body are formed. It is in fact during this early development that the human fœtus strikingly resembles that of the lower animals. The remaining six months of gestation are those of growth and maturation.

The fertilized human ovum in its development divides into two cells, these again divide, and this division of cells continues, the cells arranging themselves in a definite manner into tissues and organs. We can not follow here all the early transformations, and need only state that at about the third week of growth the body cavity begins to appear, that is, the cavities which enclose the organs of the thorax and abdomen. The fœtus is then in the cœlomate or vermian stage, that is, it now has a true body cavity and is therefore higher in construction than the cœlenterate animals (see page 643). Already in the second week the worm-like embryo begins to have a segmented body and in the following week appear four grooves on the neck of the fœtus. These grooves represent the gill slits of fishes, and the heart then also has the construction seen in fishes, that is, is two-cham-

bered. No functional gills are actually developed, however, but the structure of these vestigial gills is a clear hint that the mammalian and human lines had ancestors with this type of breathing organ, that is, among the fishes and amphibians. By the sixth week all outward appearance of the gill slits is gone; the fœtus has passed from the gilled to the lunged stage, and the fish-like heart with its two chambers has changed into the three-chambered heart seen in the amphibia, and then into the four-chambered one of mammals. The heart begins to beat in the gilled stage, but the lungs do not come into use until birth. Before then the placenta serves the purpose of respiration.

Conclusions. — "Identical in the physical processes by which he originates — identical in the early stages of his formation — identical in the mode of his nutrition before and after birth, with the animals which lie immediately below him in the scale — Man, if his adult and perfect structure be compared with theirs, exhibits, as might be expected, a marvellous likeness of organization."

"Whatever system of organs be studied, the comparison of their modifications in the ape series leads to one and the same result — that the structural differences which separate Man from the Gorilla and the Chimpanzee are not so great as those which separate the Gorilla from the lower apes."

"And thus the sagacious foresight of the great lawgiver of systematic zoology, Linnæus, becomes justified, and a century of anatomical research brings us back to his conclusion, that Man is a member of the same order as the apes." (Huxley.)

The Most Ancient Hunters *

The Ape-man of Java. — In 1891 there was discovered at Trinil, Java, in volcanic material (lapilli) a great quantity of mammalian bones, of species which are now all extinct in that region. Among these were the remains of the oldest known bones of ancient man. The geologic age of the fossils is somewhat uncertain, and most probably is earliest Pleistocene. The human remains consist of the upper part of the skull, or cranial vault, three molar teeth, and the entire left femur. Dubois, the discoverer, named this human being *Pithecanthropus erectus*, which means *the ape-man who walked erect* (Figs. 515, 516). The skull is of the long-headed (dolichocephalic) type, and has a low crown with prominent brow-ridges, the forehead is more receding than that of the chimpanzee, and the volume of the brain cavity is approximately 28 ounces. The largest cranial capacity in the higher apes does not exceed 20 ounces, while that of a normal living human is never less than 30 ounces. As the

* An interesting book in this connection, and one from which much of the information in this section is taken, is *Ancient Hunters*, by W. J. Sollas.

average human brain has a capacity of about 49 ounces, it is seen that *Pithecanthropus* must be included within the human family, and in his mental evolution had risen far higher than halfway between the apes and modern man. He is probably not in the direct line to the higher types of man, but represents a specialized and unprogressive branch which became extinct in the Pleistocene (Smith). The

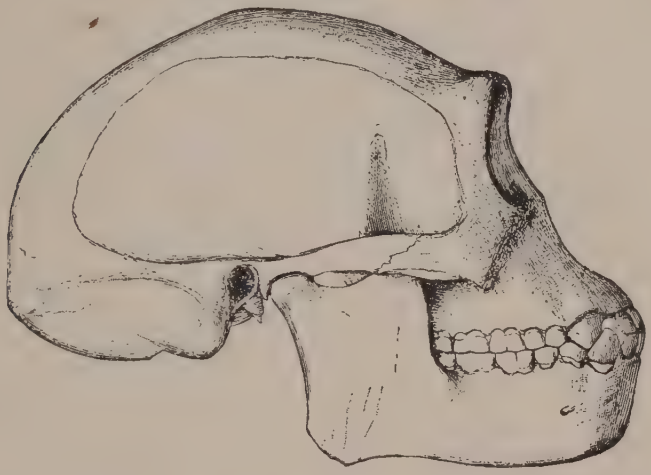


Fig. 515. — Skull of *Pithecanthropus*, the ape-man, as restored by Dubois.

femur is distinctly human, of a being that walked more or less erect, and in all probability possessed a foot very much like that of living man. The brain cavity also shows that the ape-man had probably acquired the rudiments of vocal speech. *Pithecanthropus* is estimated to have stood 5 feet 6 inches high (Fig. 516).

Eoanthropus of England. — In 1913 there was brought together the greater part of a human skull and jaw found in the plateau gravels at Piltdown, near Fletching, in Sussex, England. These remains are the oldest known of the human family in Europe and have been named the "dawn man" or *Eoanthropus*. The fragments have been carefully set together and the greater part of the skull restored by Smith Woodward of the British Museum (Pl. 39, Fig. 1, and Pl. 40, Fig. 2). The lower part of the face is decidedly prognathous or "snouty," the forehead, though narrow, is not receding, and is as steep as in modern man, the brow ridges are feeble, and the brain case is very thick, with a cavity content of nearly 43 ounces. The size of the brain, therefore, compares favorably with that of the average European, which has a content of about 49 ounces. The skull is low in proportion to length (brachycephalic), and even though

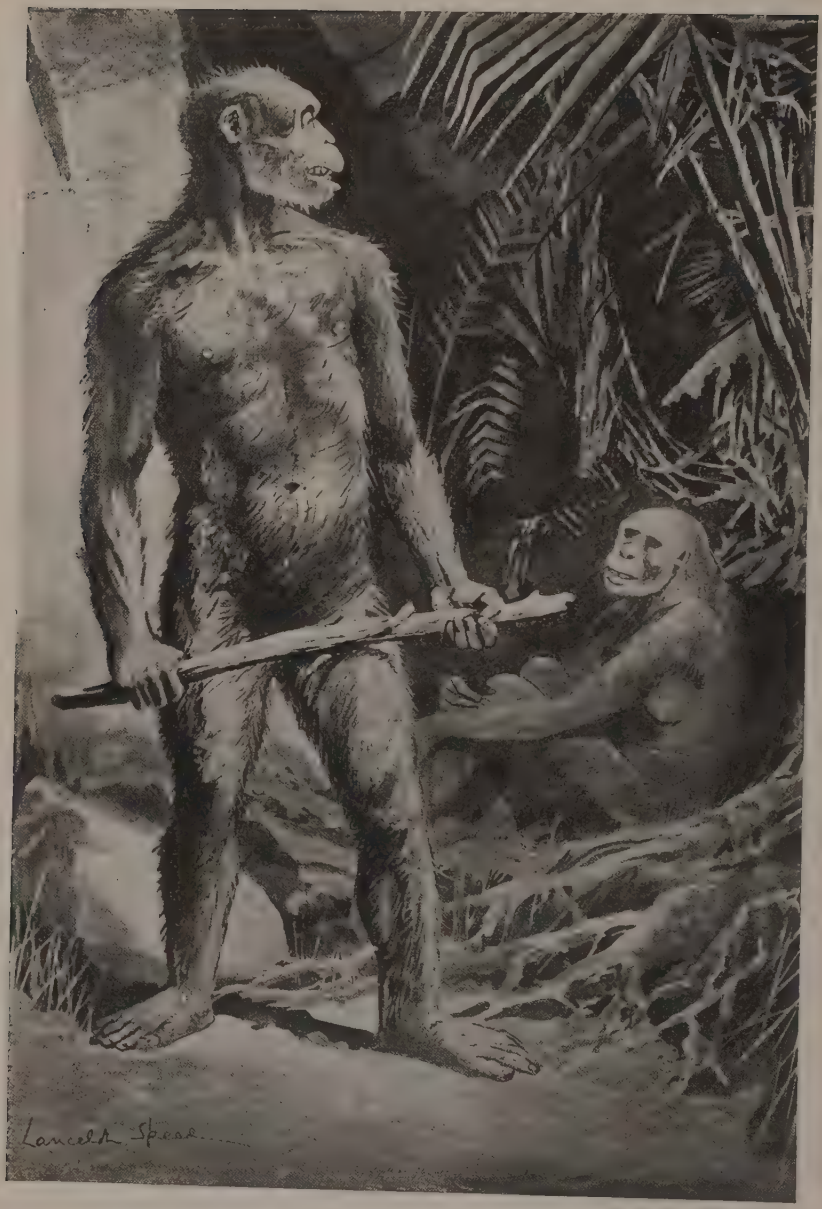


Fig. 516. — Restoration of *Pithecanthropus* by L. Speed, from Knipe's *Nebula to Man*.

it is archaic, is truly human; but the chinless lower jaw, with its large canines, is distinctly simian and very much like that of a young chimpanzee, and the neck is very thick. This strange creature, therefore, combines a human brain case with an ape's jaw. It was probably able to speak, though in a rudimentary fashion.

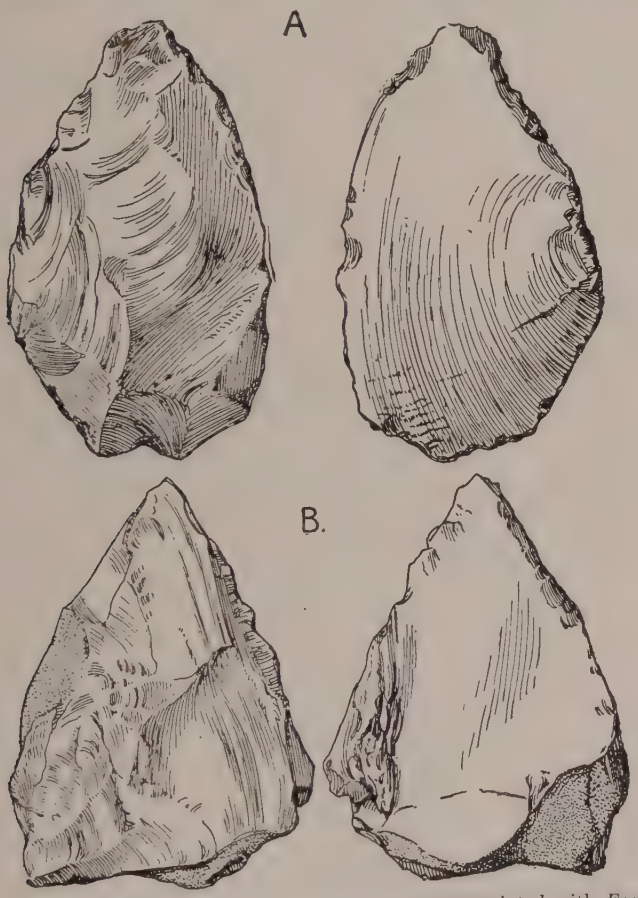


Fig. 517. — Two primitive Paleolithic flint implements associated with *Eoanthropus*, two-thirds nat. size. Each shows a coarsely flaked face and a simply flaked face. After Woodward, from British Museum Guide.

The prognathous face and powerful jaws, with their large teeth, especially the canines, show that *Eoanthropus* was a human brute, hunting and defending himself in the main with his fearful biting mouth. He was still a primitive slayer, though keener than any of his animal associates, and was destined through the manufacture of better implements to become a hunter of a higher order.

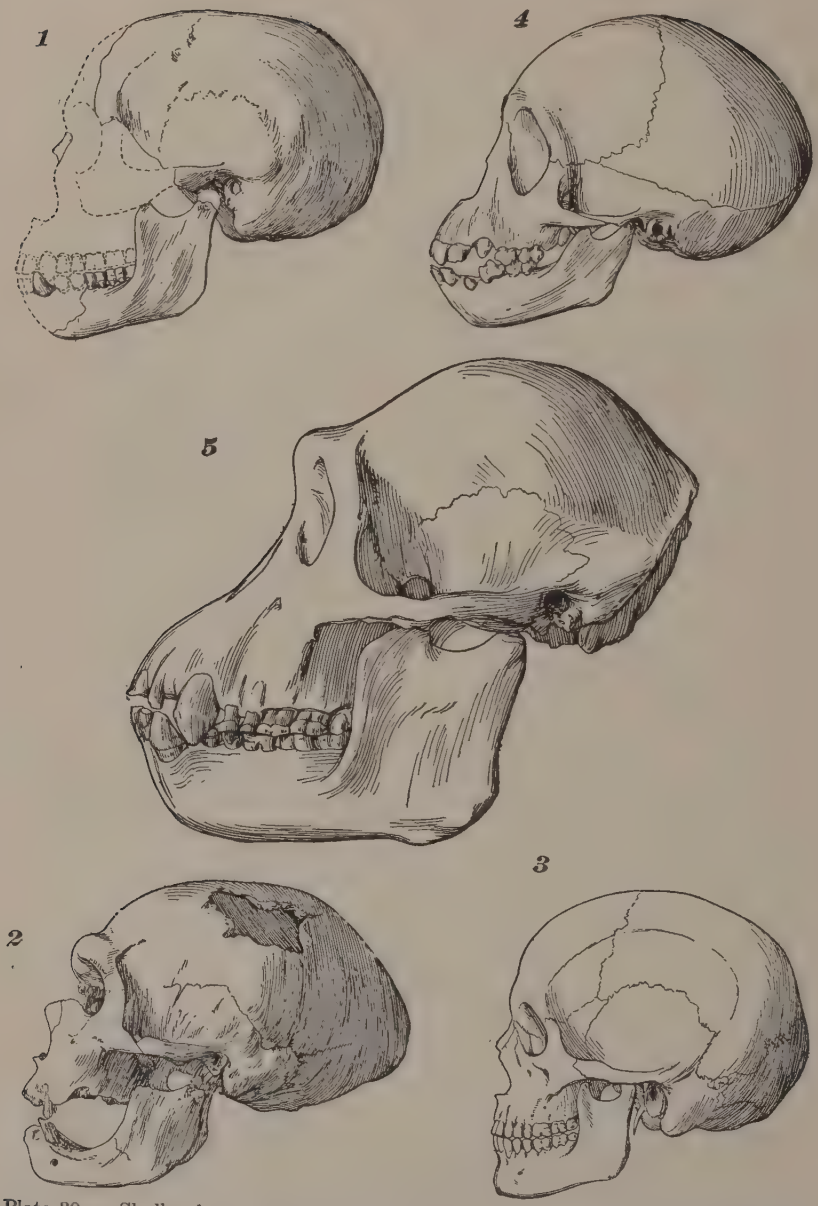


Plate 39. — Skulls of man and apes. 1, *Eoanthropus;* 2, Neandertal or Mousterian man; 3, modern human; 4, young chimpanzee without brow-ridges and more like *Eoanthropus;* 5, adult chimpanzee with marked brow-ridges and more like Neandertal man. After Woodward, from British Museum Guide.

With *Eoanthropus* were associated very ancient types of Paleolithic implements (Fig 517). The age of the plateau gravels is thought to be of the second interglacial warm time, when the hippopotamus lived in England; this is about early Middle Pleistocene (Fig. 512).

Attention should be directed here to Smith Woodward's statements that at least one very low type of man with a high forehead was in existence in western Europe long before the low-browed Neandertal man (page 971) became widely spread in this region. Accordingly he inclines to the theory that the Neandertal race was a degenerate offshoot of early man and probably became extinct, while surviving modern man may have arisen directly from the primitive source of which the Piltdown skull provides the first discovered evidence.

Heidelberg Man. — In 1907, at Mauer, Germany, not far from Heidelberg, there was found a well-preserved human jaw with all of the teeth (Pl. 40, Fig. 3). It was buried about 80 feet beneath the surface in river-deposited sand of early Middle Pleistocene age and possibly of the second interglacial warm time (Fig. 512). More recently eoliths (see below) have been found in the same stratum that held the jaw. The teeth, while powerful, are distinctly human, but the jaw bone is massive and broad and clearly more like that of an anthropoid ape. This man had no chin and was probably most closely related to *Eoanthropus*.

Eoliths. — In many places have been found large and small stones, chiefly of flint, that have rudely chipped edges and resemble weapons made by primitive man. They are found in strata of various ages as far back as the Oligocene, a time when no human being existed or for that matter any animal making stone implements. For this reason most archeologists look upon them as flints fractured by nature through such causes as rock pressure, temperature changes, or wave-pounding in the littoral of the sea.

In the ape-man, with dawning intellect, pebbles may have at first served as missiles or even as hammers. The mere striking together of stones and especially the brittle flints would lead to the discernment of cutting edges and the production of flakes that could be used for scraping, sawing, and sundering flesh and skins. At first such implements would be no better than those made by nature, and to separate the artifacts from those made through natural causes is most difficult.

No weapons have been found associated with *Pithecanthropus*, but primitive paleoliths occur in the same strata that furnished the remains of *Eoanthropus*, and "eoliths" were associated with the Heidelberg jaw. If the "eoliths" are really weapons, then most of these men must have been chippers of flint stones and makers of very rude tools (see Fig. 512).

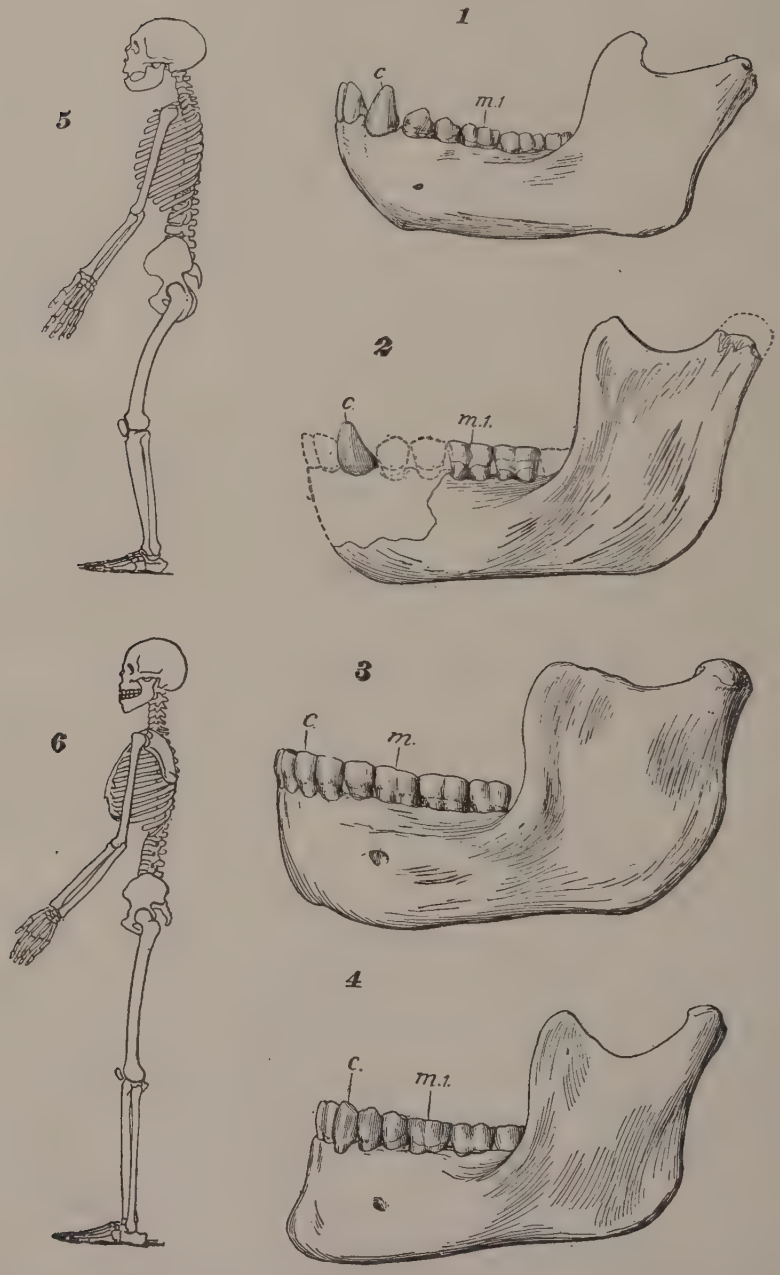


Plate 40. — Left outer sides of lower jaw of chimpanzee (1), *Eoanthropus* (2), Heidelberg man (3), and modern man (4). *c*, canine teeth; *m. 1*, first molar teeth. Diagrammatic restoration by Boule of skeleton of Neandertal man (5), and of living Australian man (6). After Woodward, from British Museum Guide.

Paleoliths. — It is a debatable question whether any human artifacts are older than the early Middle Pleistocene and the earlier questionable implements may for the present be disregarded. The oldest undoubted human artifacts are known as Paleolithic implements and among these the older Paleolithic ones are very crude in workmanship (Fig. 517). They are nodules of flint, reduced to the required shape and size by flaking with the hammer-stone, by means of oblique blows delivered to the right and left. These crude artifacts are short, thick, and irregular in form, with variable but comparatively small conchoidal fractures where the flakes were detached. The flakes obtained as by-products could also be used for small implements. For the greater part they are rude scrapers and knives, and none appear to be weapons of the chase, though their makers may have had rude wooden spears. The Neandertal men showed far more skill in the making of their artifacts, for they knocked quite large thin flakes (up to 7 inches in length) from the flint nodules and then trimmed these into the desired shape for lance-heads by finer secondary and tertiary chipping. These tools were made by the men of the Stone Age, men who were learning how to hunt animals for food and to defend themselves by their greater skill in the invention and use of improved killing devices (see Fig. 512).

Men of the Stone Age

The Older Paleolithic Hunters

Neandertal Man. — In 1856 most interesting human remains were found in a cave in the little valley known as the Neandertal, lying between Düsseldorf and Elberfeld. Since then more than fifteen other men, women, and children of this race have been found in caves and rock shelters in Belgium, France, Gibraltar, and Krapina in Croatia (Pl. 39, Fig. 2, and Pl. 40, Fig. 5). Their implements, however, are found scattered throughout western Europe and eastward into Poland, the Crimea, and Asia Minor. In France these people are known as the Mousterians and they are thought to have been the first who dwelt in caves. They lived during the last glacial episode when the climate was cool and finally cold, a time estimated to be anywhere from 60,000 to 150,000 years ago. It was the time of the bison, horse, reindeer, and mammoth, on all of which the Neandertal men subsisted. The race lived for a long time geologically (Fig. 512).

The Neandertal people (*Homo primigenius*) were a savage-looking race of stout build, short stature, averaging about 5 feet 3 or 4 inches,

with legs slightly bent at the knee, and with disproportionately large heads (Pl. 40, Fig. 5, and Fig. 518). They made fairly good stone implements and knew how to kindle a fire, for hearths occur in their cave abodes. The Australians and Tasmanians of to-day, the "most archaic types" of humanity, are their nearest relatives, and yet these savages are not descended from the Neandertal men of Europe. Huxley in 1863 said that Neandertal men possessed the most ape-like head then known, but that they were in no sense intermediate between men and apes.

The face was singular, savage, usually more or less prognathous, and unlike that of any existing race. The nose was of unusual size

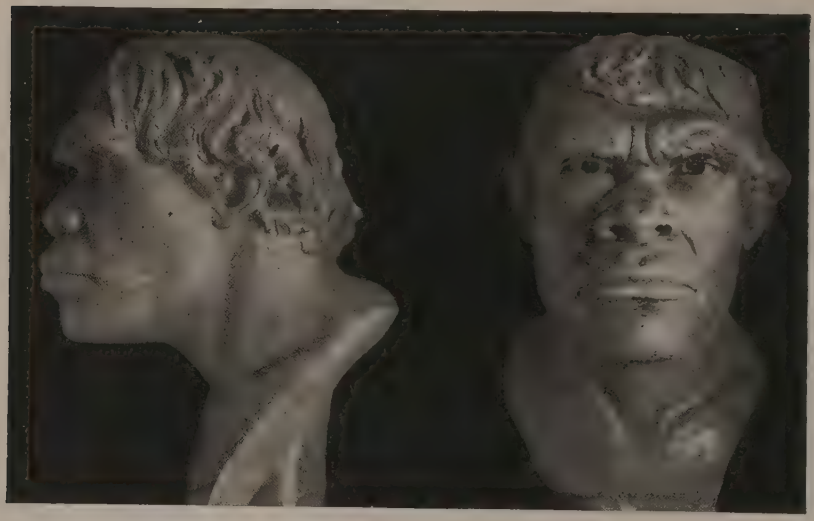


Fig. 518. — Restoration of the head of Neandertal man. Modeled by Mrs. H. Hyatt Mayer.

and wide, the upper lip very wide, and at the base of the forehead there was a very prominent and continuous brow-ridge that extended from temple to temple. It is the latter character, in fact, that distinguishes the Neandertal man from all others, though in some of the Australians a brow-ridge is also developed to a small extent. The lower jaw is heavy and massive and, as in the apes, is without a chin. The brain was unusually large. The Gibraltar head, possibly of a woman, has a capacity of about 41 ounces, while the average of Neandertal skulls appears to be 49 (in one it is 53) ounces. This average is therefore greater than in the Australian and not much below that of Europeans, whose average capacity is about 49 ounces. The hair was probably wavy.

In at least two cases the skeletons were found in their original burial places, and from them we learn that they were laid away with their implements, paints, and food, indicating a ceremonial interment and offerings of food and implements to assist the departed in the spirit world.

The Newer Paleolithic Hunters and Herders

Aurignacian Man. — We now come to men of the human species (*Homo sapiens*) who were still hunters but who possessed far greater skill in the making of stone and bone implements, and who also engraved and painted pictures of many kinds of animals in the caves of France and Spain. These were likewise of the "Old Stone Age" and appeared in western Europe at about the close of the Glacial Period, or at least 17,000 years ago, possibly even 50,000 years (Fig. 512). There were at least two races of them, a dominant one, the Cro-Magnon people, of tall stature, averaging 6 feet in height, with long arms, and long in the lower leg. They were remarkably long-headed (dolichocephalic), with a large cranial capacity ranging between 52 and 56 ounces. The face was short, the eye orbits were wider than long and depressed, and the brow-ridges were strong. The other, or Grimaldi race, shows negroid characters, its members being but 5 feet 2 to 5 inches in stature, with extremely elongated lower limbs, flat nose, prognathous jaw, and slightly retreating chin. They are thought to be allied to the living Bushmen of Africa.

The Aurignacian races appeared throughout Europe at a time when the climate was colder than it is now and when the Neandertal men were vanishing. The animals of the chase living at that time were largely the reindeer and horse, and for this reason it is also spoken of as the epoch of the reindeer. The Aurignacian implements are of the Newer Paleolithic type, that is, the workmanship of the flints is better and constantly improves with time, and the race had many more kinds of tools to serve more purposes. They also used bone for awls and ivory for skewers and ornaments, and made spears, bows and arrows, and fur garments. Themselves they ornamented with marine snail shells and teeth of mammals, and later with beads, bracelets, and other objects manufactured out of shell and ivory.

Armed with better weapons of the chase and a wider knowledge of their use, the Aurignacians were able to take better advantage of their environment. Under these circumstances, they had more ease and time for reflection, and we witness in them the birth of the fine arts. Sculpture and drawing appear almost simultaneously, and later

comes painting. This art we find preserved in the caves of France and Spain, the art of one period being overlaid by that of later times, and as time goes on the workmanship is greatly improved. Animals of many kinds are depicted, at first outlined in black (Fig. 519), then engraved on the walls and even on the ceilings of the dark caves; later were added polychromes in red, brown, black, and several shades of yellow. The pigments were of mineral origin and were mixed with grease. These artists also engraved animals on stone, bone, and ivory. The human figure appears only in the later paintings, and in these, garmented women are seen herding cattle and men chasing wild animals. Small figurines made of ivory and limestone, and usually representing nude women, are of still greater antiquity.

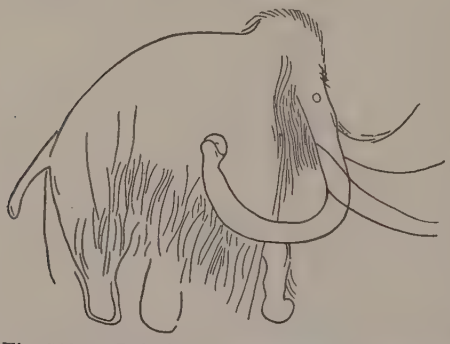


Fig. 519. — Painting of mammoth on cave wall at Combarelles, France. From MacCurdy.

Magdalenian and Later Races. — The Aurignacians were followed by the Solutréans and Magdalenians, or men of the Neolithic or polished stone period. These people not only made the same implements as the Aurignacians, but fashioned even better chipped flints and softer stones that were rubbed smooth and sometimes polished; the polishing, however, was due to use rather than to any shaping or preparatory process. The history of the race goes back perhaps 10,000 years, and while they too were hunters, they herded cattle, sheep, and goats, and somewhere about this time farming of plants for food had its origin.

The use of metals first arose in Egypt about 5000 years ago, when copper implements and ornaments were made. This period was the *age of copper*, and it was followed some 1500 years later by the *age of bronze*. The *age of iron* had its rise in Palestine about 3200 years ago and the use of the metal then spread into India and to the Mediterranean peoples. Great advances were made when humanity learned how to burn coal, and the *age of coal* began in England in the fifteenth century A.D. The last century saw the rapid development of the steam engine and we are now in the *age of electrical devices*.

Man in North America. — Nothing is known of man in North America during the Pleistocene. The red men or Indians probably migrated from Asia by way of Siberia to Alaska, and after the ice of the Glacial Period had melted away from the northern lands spread

south into Central and South America. Man has been in North America probably some tens of thousands of years, though most anthropologists believe he has been present only a few thousand years.

Birthplace of Man. — It is as yet impossible to say positively where man's transition from the ape to the human form took place. The oldest known relics of ape-man are the bones of *Pithecanthropus* found in Java, and for this and other reasons it has long been held that the race probably arose in Asia and in the cooler climes rather than in the tropical jungle. We have seen that much of central Asia was being elevated in Miocene time and that the great Himalayas rose yet higher in the Pliocene and are still rising. This time and region were, then, critical for organisms, as the climate was changing from that of the tropics to cooler and finally cold conditions, bringing on great changes among the plants and thus reacting upon the animals. Man's ancestors, therefore, had to adapt themselves to these changing conditions, and to protect themselves against the cold, clothed their bodies in the skins of the chase, and because of this covering lost their bodily hair. In addition, they had to adapt themselves to the animals and plants that remained, and many of these are not only still living in this region, but are now our domesticated animals. The ox (*Bos primigenius* into *B. taurus*), sheep, goat, pig, fowl, and pigeon are from India, while from wider Asia came the horse, camel, reindeer, elephant, peacock, goose, and ostrich. Still other forms reached Africa, and man there tamed the ass, domestic cat, greyhound, mastiff, and guinea hen. Of our domesticated plants the great majority are also of Asiatic origin. For these reasons it is thought that an ape line changed into man somewhere in central Asia, India, or China (Williston). However, the earlier evolution may have taken place farther west in the countries along the north side of the Mediterranean.

Résumé

Man, like all other living plants and animals, begins in a single, tiny, nucleated cell, and his further development is that of the Metazoa (page 415), and more especially that of the mammals and his nearest relatives, the apes. Something of this vastly long ancestral history is repeated in the first three months of each human being's existence and constitutes a metamorphosis even more wonderful and significant than the transformation of the caterpillar into the butterfly. This metamorphosis, beginning in the protozoan or single-celled stage, passes rapidly through others comparable to the lower forms of the Cœlenterates or hydra-like metazoans (page 408), and to the annulate, worm-like, gill-breathing ancestors of all vertebrates known as the half vertebrates (see *Balanoglossus*, page 691). Next appears the fish-like stage, when the functioning heart and the vestigial gills are comparable to the same organs in fishes; then the heart is transformed into the type seen in amphibians and next into that of mammals. At this time of development it is almost impossible to distinguish the human fœtus from that of other mammals, but the

latent ancestral history impressed upon the embryo from the very beginning goes on reproducing more or less blurred characteristics of the apes and man.

Among the mammals the human line had its origin in the lemurs of the Eocene of North America, which gave rise to the monkeys that spread over the greater part of the early Tertiary world. The European branch of monkeys, spreading into Africa, there gave rise to the small apes of the late Oligocene of Egypt. *Paleopithecus* spread across the Mediterranean land bridge and in the Miocene of Europe developed into the gibbons of the Euro-Asiatic countries. Out of the latter in late Miocene time originated the large-bodied apes, giving rise in the Pliocene to the several independent genealogies expressed in the orangs, chimpanzees, gorillas, and humans. The missing links between ape and ape-man will be recovered in Pliocene strata somewhere in Europe or in Asia.

We have seen that the bipedal ape-man *Pithecanthropus* was in existence in the earliest Pleistocene, a time estimated by geologists to be somewhere between 400,000 and 1,400,000 years back of the present. Then there is no record of human bones for a long time, but if the "eoliths" are of human workmanship they are evidence of man's presence in western Europe throughout the Pleistocene. About early Middle Pleistocene time human bones are again in evidence in England and Germany, but it is not until about 150,000 years ago that remains are common enough to make a fairly continuous record into the present. Throughout nearly all of this time the record is one of very slow mental evolution from the ape-man *Pithecanthropus*, with decided animal instincts, into *Eoanthropus*, and then into the possibly degenerate large-headed savages known as the Neandertal men, who lived in Europe for a long time (Fig. 512). Even at this early time (60,000 to 150,000 years ago) man knew how to kindle fire, and that a religious instinct was present is plain from the respect paid to the departed by laying them away in graves with ceremony. The fine arts arose with the Aurignacians about 20,000 years ago, and the modern state of human society and primitive farming had their rise about 10,000 years back of the present. Human mentality now dominates the organic world, and to it all creation will soon be more or less subservient. Invention and adaptation will eventually lead man to use and control the physical and vital forces and he will be master of himself and his environment.

To quote again from Huxley: "Our reverence for the nobility of manhood will not be lessened by the knowledge that Man is, in substance and in structure, one with the brutes; for, he alone pos-

sesses the marvellous endowment of intelligible and rational speech, whereby, in the secular period of his existence, he has slowly accumulated and organized the experience which is almost wholly lost with the cessation of every individual life in other animals; so that, now, he stands raised upon it as on a mountain top, far above the level of his humble fellows, and transfigured from his grosser nature by reflecting, here and there, a ray from the infinite source of truth."

CHAPTER LVI

EARTH HISTORY IN RETROSPECT

Development of the Earth

Origin of the Universe. — Astronomers and historians of the earth and of its life are impressed with one fact above all others, namely, the constant changeableness of the entire universe, the constant evolution of all matter. In the stars and nebulæ the changes are indeed exceedingly slow as measured by the comprehension of the human mind, but in the parts of each entity the interactions may be swift or long continued, leading to the establishment of new aggregates and even of new worlds. Stability is most enduring in the more or less condensed masses, and as these are made up of elements, they remain stable only so long as their environment is unchanged. Everywhere matter appears to be essentially alike, though varying from extremely tenuous or gaseous to condensed solid states. Accordingly the internal aggregation of the parts must vary, depending upon the disruptive state of the matter, so that the very tenuous luminous bodies give testimony of but a few elements, while the more solid ones evince essentially the same elementary constituents as those of the earth.

We see changing before our senses the radioactive elements, and further observations of the heavenly bodies convince us that all interact upon one another, changing their environment and therefore their states of internal aggregation. Great masses of matter for millions upon millions of years continue to change and condense from a gaseous luminous state to a variably solid one, a star or sun, and even though all the astronomic bodies are spaced by distances beyond human comprehension, their masses and their momentum may yet bring them close enough to exert decided attraction upon one another. When the approach is sufficiently near, the tidal interactions between the affected masses may become so great as to produce a stellar explosion of variable magnitude in one or both, and there is born a new star or a spiral nebula. Among the millions and millions of suns or stars there are probably more than a million of these disrupted bodies, the nebulæ, and each one of them is evolving toward a constellation. In this way arose the constellation of the sun, which is composed of the planets and their satellites.

Origin of the Earth. — What the cosmic history of the earth has been can only be conjectured from a study of the nebulæ and their probable evolution. This knowledge leads to the hypothesis that the earth began as a large knot of solid matter, situated in one of the arms of a spiral nebula, around which revolved in elliptic orbits innumerable smaller bodies, the planetesimals. The nucleal earth and moon in the course of millions and millions of years attracted to themselves these planetesimals and so grew from small diameters to sizes even somewhat greater than they are at present. As the earth's mass became greater and its attraction stronger so as to hold the light escaping gases, it gradually came to have an atmosphere and a limited hydrosphere.

Periodic Rising of Mountains. — The periodic readjustment in the earth-shell of North America is recorded by at least fourteen times of mountain making (Fig. 520). Eight of these, of lesser import, are the disturbances (Green Mountains, Taconic, Caledonian (in Europe mainly), Shickshockian, Quachita, Palisade-Chitistone, Sierra Nevada, and Cordilleran Intermontane), which took place during the closing stages of as many periods (Waucobian, Ordovician, Silurian, Devonian, Tennesseian, Triassic, Jurassic, and Comanchian). At each of these times folded mountains were thrown up by horizontal compressive movements in the earth-shell, and the area affected by each disturbance varied in length from at least 1000 miles to more than 1500 miles. The other six mountain-making movements are of far greater significance; these are the revolutions (Laurentian, Algomian, Grand Canyon, Appalachian, Laramide, and Cascadian), which close the six eras (Archeozoic, Early and Late Proterozoic, Paleozoic, Mesozoic, and Cenozoic), into which all geologic time is now divided (Fig. 520). These are also the " critical periods " in the history of the earth, when mountains are made in most or all of the continental masses. The lands are then highest above the strand-lines of the oceans, and as the climates are drier, cooler, or even cold, it follows that these times are also critical for the plants and animals then existing.

When the earth-shell folds, the deep-seated molten rocks follow into the zones of relieved pressure, and, rising to higher levels, inject themselves into the sedimentaries as the more or less large bathyliths, metamorphosing the enveloping rocks. Not only this, but as they rise they may melt and take into themselves the covering formations and so eventually gain the zone of fractured rocks, where the liquid magmas push through these openings to the surface, there to give rise to volcanoes and lava flows. Over and over again

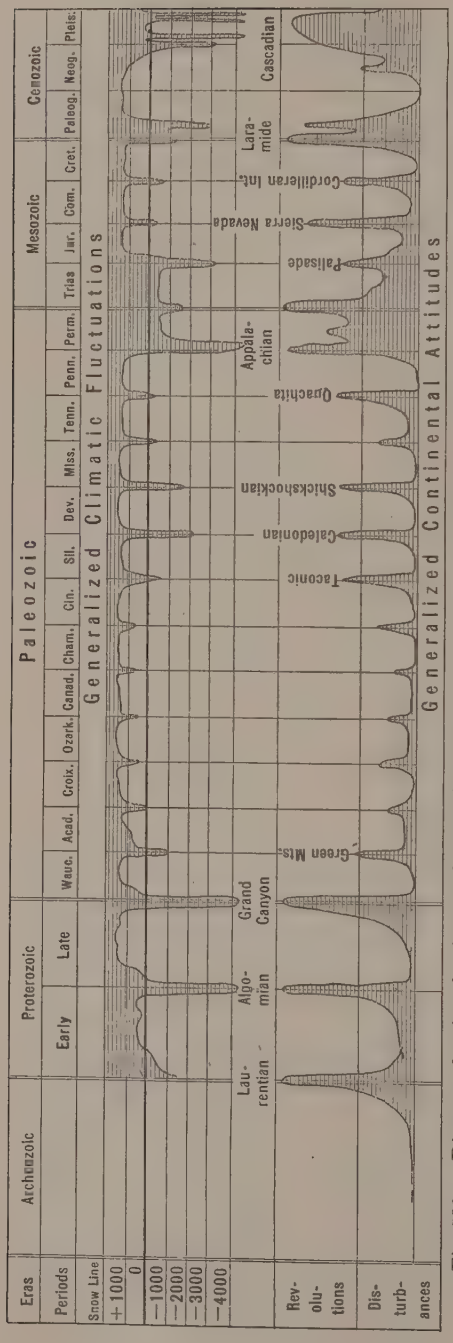


Fig. 520. — Diagram showing the times and probable extent of the more or less marked climatic changes in the geologic history of North America, and of its elevation into chains of mountains.

it is seen that volcanoes accompany mountain making and other crustal movements.

All of the young mountains of the present earth's surface are situated close to the margins of the continents or else in the areas of long enduring geosynclines. According to the law of earth wrinkling, the mountains rise out of the former sinking and loading geosynclines, the latter being the weak zones in the lithosphere and the places where the shortening of the earth-shell is taken up by folding and overthrusting. In North and South America and Africa all of the folded mountains are situated near the margins of the continents; while in Europe and more especially in Asia the young mountains are more or less marginal, but the older ones are inside of these where former geosynclines have been.

Origin of the Atmosphere and Hydrosphere. — According to the planetesimal hypothesis, there was a time when the earth's mass was too small to hold an

atmosphere. This was during the nuclear stage and before the earth had attained the size of Mars, which has a diameter of 4200 miles. When this size was reached, our planet began to hold a thin atmosphere. Ever since volcanic action began — and it is assumed to have had its origin even before the earth had attained a diameter of 3000 miles — the volcanoes and thermal springs have been adding gases and water vapor to the atmosphere. With an atmosphere present it is natural to assume the presence of a hydrosphere and areas of standing waters. However, as long as an abundance of planetesimals continued to fall in upon the earth, it is questionable if there could have been seas and ocean basins and any marked weathering processes. On the other hand, the quantity of salt in the present oceans and in the strata appears to be evidence indicating that the weathering processes and the accumulation of salt by the oceanic waters may not have begun much earlier than the Archeozoic.

Origin of Oceans and Continents. — When the earth had attained to about its present diameter, in the Archeozoic, its atmosphere gave rise to the processes of solution, to weathering of rocks, and to the washing together of sediments formed on the earth's face, and the resulting finer materials together gravitated to lower places and eventually into the oceanic basins. The latter depressions probably are primarily due to the separation of the molten magmas during the formative eon into lighter or continental and heavier or oceanic portions. Therefore the oceanic basins have as a rule tended to sink and to follow more decidedly the shrinking centrosphere, thus becoming the negative areas, while the lands, somewhat lighter in specific gravity, become more so through the solution processes, resulting in the rising protuberances of the lithosphere, the positive areas. Even though the oceans have continued to attain greater depth, the increasing volume of sediment and water has demanded enlarging basins, and some of the required space has been taken from the continents. In this way the great northern transverse continent, Eria, and the similar medial one, Gondwana, were transformed into the longitudinal continents of the present.

Permanency of Oceanic and Continental Areas. — Since the beginning of Paleozoic time the oceanic basins and the continental masses have been more or less permanent. The permanency, however, is not rigid but is rather flexible, most rigid in the oceanic areas and more flexible in the continental masses. There is, moreover, a periodic flexibility in the oceanic areas, for many times have they

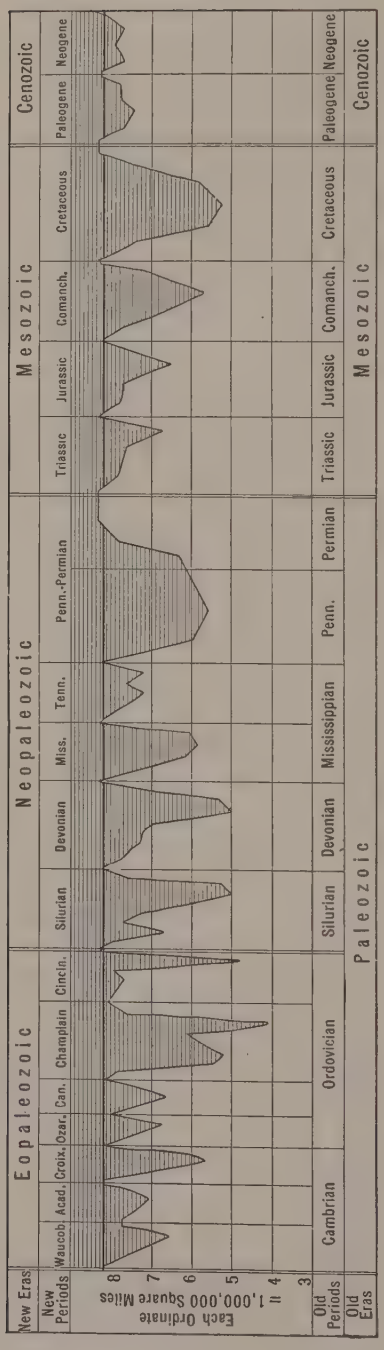


Fig. 521. — Diagram showing the time and extent of the known floods that have inundated North America since the close of the Proterozoic era.

spilled their waters widely over the land in shallow inundations. Over and over again the flooded lands have reasserted themselves above the general water-level because of renewed oceanic subsidence and the withdrawal of the waters. These are the main features in the present theory of the permanency of continents and oceans, a hypothesis that is less rigid than the original one of Dana (1846).

Periodic Continental Flooding. — Between the comparatively short intervals of mountain making and crustal unrest occur the long times of erosion, peneplanation, and more or less flooding of the continental masses by the oceans. Since the close of the Proterozoic, North America, and especially the United States, has been widely flooded by warm and shallow marine waters at least twelve times (Cambrian, Ordovician, Cincinnatian, Silurian, Devonian, Mississippian, Pennsylvanian, Triassic, Jurassic, Comanchian, Cretaceous, and in an oscillatory way during the Tertiary), and probably not less than seventeen times (two additional floods in the Cambrian, two in the Ordovician, and one in the Mississippian). These shallow-

water spreadings begin in a small way, grow to greater dimensions throughout a very long time, and then, declining, recede far more rapidly than they came. They vary in areal extent up to 4,000,000 square miles (Fig. 521).

During the Paleozoic nearly all the seas were of the epeiric kind, with the greatest spread of water first from the Arctic, next from the Pacific, and in least amount from the Atlantic. On the other hand, the number of floods was greater from the south than from the north, and the waters were most persistent in the Appalachian and Cordilleran subsiding geosynclines, the sites on which eventually arose the Appalachian and Rocky Mountains.

Imperfection of the Geologic Record. — It is a well-known fact that the geologic record is fragmentary and local in preservation and that even after correlating all the parts and through them restoring the events of the geologic past for the entire world, the final result, the geological time-table, still remains very imperfect. How incomplete the records are in Stratigraphic Geology is made clearer from one generation of geologists to another, since where seventy years ago geologists knew of but three eras, there are now held to be six; and in the same time the number of known periods has more than doubled. As the major time divisions have been doubled in number in seventy years, it is apparent how inadequate must be our knowledge of the entire earth history. In another half-century the geological time-table will doubtless be again as long as it is now, but this perfecting of knowledge will probably not come through the discovery of many more new eras and periods, but rather through the finding of many more of the minor time elements, the formations, which go to make up the systems of rocks. The long middle times of the periods are even now far better known than are the opening and closing events of these divisions.

Age of the Earth. — From the preceding statements, it follows that any estimates as to the age of the earth stated in years and based upon the known sedimentary record can not be much better than guesses. Further, we do not yet know satisfactorily the rate of erosion or sedimentary accumulation. Data have been gathered as to the mean annual rate of sedimentary discharge for nine rivers and it varies between 1 part of sediment in 291 of water for the Rio Grande and 1 part in 10,000 for the Uruguay. Harker states: "The highest figure is thus thirty-four times as great as the lowest" and "a mean of nine figures so discordant can not afford any information of quantitative value."

Hutton, one of the founders of Geology, said more than a century

ago that geologic time had no " vestige of a beginning, no prospect of an end." In other words, that geologic time was infinite. A reaction from this belief came in 1862 from the physicist, Lord Kelvin, who held that as our planet was continually losing energy in the form of heat, the globe was a molten mass somewhere between 20,000,000 and 400,000,000 years ago, with a probability of this state occurring about 98,000,000 years ago. Finally in 1897 he concurred in Clarence King's conclusion that the globe was a molten mass about 24,000,000 years ago. Both of these conclusions, however, were wrought out under the Laplacian hypothesis, and now many geologists hold that the earth never was molten. While geologists have not been able to fit their evidence into so short a time, they have ever since been trying to keep their estimates within the bounds of Lord Kelvin's older calculations. Walcott, in 1893, on the basis of the stratigraphic record and the known discharge of sediment by rivers, concluded that 70,000,000 years had elapsed since sedimentation began in the Archeozoic. Sir Archibald Geikie places the time at 100,000,000 years, and most geologists have tried, although with difficulty, to fit the record within these estimates.

Since the discovery of radium, all of the calculations previously made have been set aside by the new school of physicists, and now geologists are told that they can have 1,000,000,000 or more years as the time since the earth attained its present diameter. " A study of the various radioactive elements contained in minerals and rocks," says Harker, " has shown that it is possible, in certain favorable cases, to calculate directly their age in years." Thus it has been estimated that the Eocene iron-ores of Antrim in Ireland are 30,000,000 years old, and that those of the Carboniferous limestone of Cumberland, England, are 140,000,000 years in age. The igneous rocks of Devonian time about Christiania, Norway, show an age of 185,000,000 years, while " Archean " rocks have values ranging between 1,000,000,000 and 1,600,000,000 years. Even if finally it shall turn out that the physicists have to reduce their estimates as to the age of certain minerals and rocks, geologists nevertheless appear to be on safer ground in accepting their estimates than those based either on sedimentation, chemical denudation, or loss of heat by the earth.

Climatic Variations. — We are living at a time when the earth has marked climatic differences, varying between very cold polar climates and hot moist or dry tropical conditions. This has, however, not always been the case, for not long ago geologically the temperature was even colder than it is now, and most of the climates

of the past have been warm and fairly equable the world over. The warm climates persisted during long geological ages, and even though there were zonal belts and fluctuations in the temperature, the polar areas were usually inhabited by plants and animals of kinds that were addicted to winterless environments. These temperature fluctuations were greatest during the closing and opening stages of the periods, and the atmosphere was then also often drier (Fig. 520).

The long warm times were separated by short periods of cool to cold climates. Geologists now know of seven periods of decided temperature changes (earliest and latest Late Proterozoic, Silurian, Permian, Triassic, Cretaceous-Eocene, and Pleistocene) and of these at least four were glacial climates (both Proterozoic times, Permian, and Pleistocene). The greatest intensity of these reduced temperatures varied between the hemispheres, for in earliest Late Proterozoic and Pleistocene time it lay in the northern, while in latest Proterozoic and Permian time it was more equatorial than boreal. Cooled climates occur when the lands are largest and most emergent, during the closing stages of periods and eras, and cold climates nearly always exist during or immediately following revolutions, when the earth is undergoing marked mountain making.

Progress of Life on the Earth

Appearance of Life. — We have seen that the earth began to hold a thin atmosphere when it had reached a diameter of about 4200 miles, but it is not known whether there were then or for a long time afterward standing bodies of water permitting life to originate in them. Further, it is not known what the temperature then was, or whether it was equable enough for life to have existed. Under these circumstances it is useless to speculate on the origin of life or what its nature may have been previous to the Archeozoic, the time when the geologic record begins.

Life of the Archeozoic and Proterozoic Waters. — At the very base of the geologic record, in the Archeozoic, the rocks testify to a world with about the same physical environment as that of subsequent time. There were oceans and continents, an atmosphere charged with water vapor and carbon dioxide, erosion and solution materials, and the formation of mudstones, sandstones, limestones of vast thickness, carbonaceous shales, graphites, and iron-ores. There are, however, no discernible or undisputed fossils, but that life was present in the marine waters is attested by the carbonaceous shales and the great amount of graphite. It is therefore assumed that the Archeozoic, the " Age of Unicellular Life," was a world of

organisms composed in the main of Protophyta and Protozoa. As Archeozoic time was very long, the unicellular life of the earlier ages could readily have evolved into higher forms in the later periods. It is therefore postulated that there were also many tiny forms of multicellular plants and animals present in the later Archeozoic. Among the latter were globules of cells resembling minute mulberries (morulæ), little hollow sacs with the cells arranged in two layers (external and internal) like the well-known planulæ and gastrulæ of the living world, and more complicated structures, the beginnings of the higher animals that have a true body cavity (cœlomate larvæ). (See Fig. 522.)

Throughout the Proterozoic rocks, known marine fossils are indeed scant, and yet we have learned more of Proterozoic fossils in America through the researches of Walcott during the past fifteen years than from the previous endeavors of all other geologists. The harvest, however, is still small, but we can say that we know of an abundance of marine algæ, some radiolarians, and tubes and burrows made by annelids. If we knew no more than of the occurrence of annelids, this would be a great deal, for their presence in the Proterozoic means the existence of the more lowly organized sponges, cœlenterates, and worms. However, that there were many other kinds of marine invertebrates is indicated by the highly varied life found in the oldest Cambrian strata. In fact, the opening period of Paleozoic time shows that more fundamental evolution among the marine invertebrates had taken place up to this time than subsequently. (See Fig. 522.)

Paleozoic Marine Life. — In the Lower Cambrian we find established all of the main phyla of invertebrates, and as the fishes appear in advanced forms in the Middle Ordovician, it follows that even the vertebrates had their origin previous to that time. Moreover, the trilobites are members of the highest phylum of invertebrates, the arthropods, and are hence the highest expression of skill and intelligence in a most ignorant world of invertebrates (Fig. 522).

In the Ordovician seas appear the agile carnivorous cephalopods and the first fishes. With the rise of the former goes the decline of the defenseless trilobites, and slowly they pass out of existence, vanishing altogether with the Paleozoic. The active cephalopods rise into dominancy in the Ordovician and Silurian, when the fishes are beginning their ascendancy, and even though the former do not represent the highest type of animal evolution and mentality, in the later Paleozoic they still continue to evolve into the goniatids and the highly varied ammonids, that in turn persist to the end of

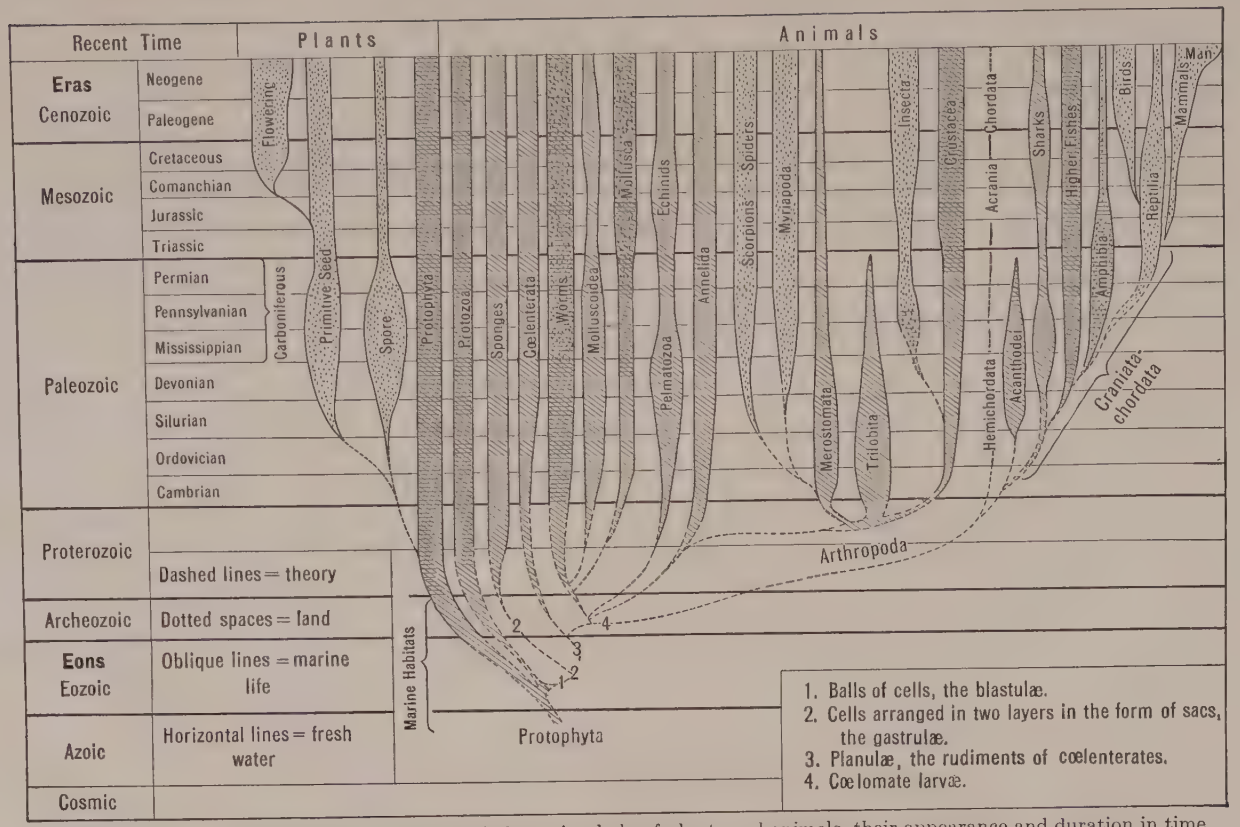


Fig. 522. — Diagram showing the genealogies of the main phyla of plants and animals, their appearance and duration in time, and their essential habitats.

Mesozoic time. The vast majority of Paleozoic marine animals, however, are sessile and vegetative and feed upon the microscopic bios that is brought to them by the water currents and other fainter currents generated by the organisms themselves. The bottom-living sea-weeds furnish food for the prowling vegetarians.

Rise of Land Floras. — So far we have been tracing the evolution of life in the seas and oceans; now we must take up the appearance of organisms on the lands, and first, of the land floras. Previous to the Ordovician we know of no land plants and the vascular or woody kinds appear for the first time toward the end of this period. It is not, however, until the Middle Devonian that they are sufficiently common to enable us to speak of land floras. Then we learn that evolution among them had progressed far, for trees are present, some of which must have been 30 or more feet tall. This, the first land flora, goes on evolving and in the Pennsylvanian attains its maximum development in variety and stature. Our knowledge of the vegetation of this time, however, is restricted to that of the low-lands and the swamps, and practically nothing is known of the upland floras. They are in the main spore-bearing plants, of rapid growth and with soft and spongy woods; while many kinds of seed-bearing shrubs and trees are present, their flowers are small and unattractive. Among the lycopods occur great trees over 100 feet tall, with trunks reaching more than 3 feet in diameter. The climate of the time is warm and moist, and as spores are microscopic and therefore very light, the winds carry them everywhere, with the result that the plant assemblages of the Pennsylvanian are world-wide in distribution and the flora is hence spoken of as cosmopolitan. (See Fig. 522.)

In the Permian the greater part of this interesting mild climate flora is either destroyed or forced to evolve into hardier kinds because of the ice age of the time. A new flora then arises in the southern hemisphere, consisting in the main of modern ferns, conifers, and cycads. It is at home on Gondwana Land and develops into the second cosmopolitan flora, which dominates the earlier half of the medieval world. Finally, the modern flora takes possession of the world early in Cretaceous time. With it come beautiful flowers, sweet odors and honey, a greater abundance of fruits and nuts, and consequently better homes and more varied foods for an enlarging world of insects, reptiles, birds, and mammals. Finally, in the early Tertiary the grasses and cereals take their ascendancy, and since the Miocene grassy plains have been plentiful and on their bounty has developed a new world of grazing mammals (Fig. 522).

Rise of Insects. — The water-breathing Paleozoic trilobites gave rise, it is thought in the Devonian or possibly even earlier, to the air-breathing insects, but none of the latter are as yet known before the Pennsylvanian. This earliest insect world, still largely addicted to a water habitat in its larval growth, was a strange one of very large forms, some resembling dragon-flies, one of which measured 29 inches across the wings, while most of them were ancestral or actual cockroaches, the giants attaining a length of 4 inches. They were carnivorous and herbivorous in habitat and developed to maturity without passing through a series of larval changes. The cold climate of the Permian, however, overwhelmed them as it did the spore flora. In the struggle for existence only those stocks of insects remained that had learned how to hibernate through the winters and in their adaptations were transformed into new orders. They were the ones that first introduced into their life histories those wonderful metamorphoses now seen in the transformation from maggot into fly and caterpillar into moth or butterfly. With the changes in the Mesozoic floras went other modifications in the insects, and with the rise of the flowering plants, birds and mammals appeared the adaptations of honey-sucking, the pollinating of flowers, the development of body parasites, and blood feeding.

Appearance of Animals on the Lands. — We have seen that the lands were hardly fit habitats for animals before the Devonian because of the scantiness of vegetation. With the Middle Devonian, at least the moist places and the swampy areas abounded in plants and in their presence there were food and new homes for the ever-widening circles of life. In the fresh waters, however, favorable habitats for the larger organisms were established much earlier, probably even as early as the Cambrian. This statement is based on the fact that in the Middle Ordovician there occur specialized fishes, of the bony-skinned or ostracoderm type, and even though their remains occur in marine strata, it is held that they lived in the estuaries and rivers of that time. (See Fig. 522.)

Lung-fishes are known in many forms in Silurian and Devonian times, but how they changed their paired fins into the limbs of the higher vertebrates still remains unsolved. However, in the Upper Devonian rocks occurs the track of a large amphibian, testifying that this change had been made and that amphibia having the form of the living mud-puppies were then in existence. Further evidence fails us until the Pennsylvanian, where we meet with many limbed and limbless amphibia, of small size, and with armored heads, — the stegocephalians. In the Permian there are much larger forms, most

at home in water and but poorly adapted to a permanent abode on the land because of their sprawling type of limb. Associated with them, however, are many kinds of reptiles that are still amphibian in appearance, but more active, agile, and wholly restricted to life upon the dry land. This is a mighty change. Next the reptiles are struggling to conquer the lands, where there is an abundance of food, but to accomplish this fleet-footedness is a necessity. Hence the handicap of sprawling legs and belly-crawling in some forms is overcome by raising the body above the ground and supporting it upon pillar-like limbs. The need for this is heightened by the fact that the continents of later Permian time are cool or arid and therefore food and drink are scarce and long distances apart. As a natural consequence the running animals take their ascendancy in this period and later give rise among others to the dinosaurs.

Vertebrates of the Medieval World. — With the Triassic the lands were captured and completely dominated by the reptiles and more especially the dinosaurs. In the Comanchian the latter developed into dimensions and tonnage never attained before or since among land animals, for 37 tons of animated flesh made up *Brontosaurus*, the thunder saurian, and *Diplodocus*, though somewhat lighter, reached 80 feet in length. Senseless brutes they were, for their individual brains weighed about one pound. Their great mass and low mentality were their undoing, and all dinosaurs, large and small, probably vanished with the Mesozoic, at a time when greater skill was coming into the animal world.

Out of the small and agile dinosaurs arose two dynasties of warm-blooded descendants which further clothed themselves in feathers and fur respectively so that they might the more easily preserve the heat and therefore the energy of their bodies. The egg-laying mammals were the first to arise in the Triassic, while the birds, appearing in the Jurassic, have never become a dominating tribe among animals, probably because of their small bodies and light weight, so necessary for flight. On the other hand, the evolution of the mammals was slow throughout the Mesozoic and all of them remained small, maintaining themselves in obscurity, and it would appear essentially in the forested areas. With the rise of the modern floras in the Cretaceous they fared better, but not until the dinosaurs vanished did they come forward as the dominating force among organisms. (See Fig. 522.)

Rise of Giants. — Ever since the Cambrian the organic world has had its pygmies and giants. The healthy mean among animals and the rise of new stocks lie among the small and unobtrusive, and the

vital world of any time may be divided into three categories: the static or slightly changing, the active progressives, and the sluggish and lazy, leading into the degenerates.

Large size may appear in any one of these groupings, but there is a marked tendency to increase in size among the active types, the progressives, which are constantly reaching out for more food. They rise into ever greater size, and suddenly vanishing with changed environments, leave no progeny to continue their ancestral parentage, and the other small and inconspicuous stocks take their places. This form of evolution has recorded itself so often that but a few of the more striking instances need be mentioned. The average length among trilobites is about 1.5 inches, and yet stock after stock attains to several inches and giants appear many times in forms ranging from 12 to 27.5 inches. Among the ammonites the average diameter is about 3 or 4 inches, but many are known a foot across and even as large as 7 feet, with tubes from 20 to 35 feet long. The story is similar among the fishes, ichthyosaurs, plesiosaurs, and whales of the seas and oceans, and on the lands several stocks of dinosaurs are conspicuous by their great size. Among the Tertiary mammals, there are many similar ascendancies, but we need mention only the evolution of the horses, camels, and proboscidians.

Rise of Mentality. — Mentality is of extraordinarily slow increase among the animals of the seas and oceans, and on the land, beginning with the Devonian, it is also slow, though faster than in the water. The environment in Neptune's realm is far more equable and there is no plane here in the sense of the surface of the land. Therefore the struggle for existence is far harder on the continents where the climate constantly varies and the organisms more often encounter one another. There is a steady but small increase of brain among the land vertebrates from the amphibia of the Pennsylvanian into the egg-laying mammals of the Mesozoic. The rapid development of mentality, however, comes in later Eocene time, when in most stocks of placental mammals there is increasing power of discernment and better adaptation to the environment. The culmination of the brain in size and complexity of structure is among the anthropoids, beginning in the lemurs, monkeys, apes, ape-men, and reaching its climax in man. What this difference is may be strikingly illustrated by the brain weight of man, which is about 2 pounds to 100 of flesh, contrasting with the giant dinosaurs of the Mesozoic, which had from 2.5 ounces to less than 2 pounds of brain with from 5 to 37 tons of body weight.

Our retrospect may close as it was begun, in wonderment at the ceaseless change of all things, from man to the grandeur of the face of the earth. Whence has it all come, what does it all mean, and to what great things is it all tending? These will ever remain the questions of finite man, in his ceaseless endeavor to grasp the significance of the infinite.

APPENDIX A

MINERALS IMPORTANT GEOLOGICALLY IN ROCKS AND ORES

Introductory. — For the benefit of those who have had little or no previous training in mineralogy, the following brief description of the chief kinds of minerals, which have been mentioned in this book and are important geologically in rocks and ores, is appended. As has been shown in the foregoing pages they are the ones which mainly compose the rocks and soils and take part in important geological processes. If time permits, and the student is unfamiliar with them, it would be well for him to begin his course with some study of the descriptions here given, and he should have the opportunity of seeing and comparing representative specimens of them.

The most important rock minerals may be listed as follows:

Calcite, $CaCO_3$
Chlorite, $H_8(MgFe)_5\ Al_2Si_3O_{18}$
Clay (Kaolin), $H_4Al_2Si_2O_9$
Dolomite, $(CaMg)CO_3$
Feldspars, $KAlSi_3O_8$, etc.
Gypsum, $CaSO_4 \cdot 2\ H_2O$
Hematite, Fe_2O_3
Hornblende, $CaMg_3(SiO_3)_4$, etc.
Limonite, $2\ Fe_2O_3 \cdot 3\ H_2O$
Magnetite, Fe_3O_4
Micas, $H_2KAl_3(SiO_4)_3$, etc.
Pyroxene, $CaMg(SiO_3)_2$, etc.
Quartz, SiO_2
Rock-salt, $NaCl$
Serpentine, $H_4Mg_3Si_2O_9$
Siderite, $FeCO_3$
Talc, $H_2Mg_3(SiO_3)_4$

By observing the chemical formulas of the above minerals, some of which represent only one variety of what is really a group, it will be seen that they comprise silicates, oxides, and carbonates of the metals, with one sulphate and one chloride, which are of lesser importance. The silicates, which are compounds of metals with silicic acid (oxide of silica, SiO_2) form the bulk of the minerals which make up the massive rocks constituting the outer shell of the earth, and upon which the sedimentary formations rest, and also of the erupted volcanic rocks. Mingled with the silicates are smaller amounts of oxides, chiefly those of iron and silica. These minerals are for the most part anhydrous, that is, devoid of combined water. The carbonates and hydrated oxides and the sulphate are chiefly in the relatively thin films which the sedimentary rocks form on the surface of the globe. The salt is mostly in the sea. Hydrated oxides,

and silicates, and also carbonates, are the result of the action of weathering and the circulation of water and other chemical agents upon rocks composed of anhydrous minerals, and are therefore found in the outermost zone of the crust where these agencies are at work; they occur in metamorphic and sedimentary formations.

Physical Properties of Minerals. — There are certain important physical properties of minerals which serve to characterize them and to distinguish them one from another. These are, *crystal-form*, *cleavage*, *color*, *hardness*, and *streak*.

With regard to *crystal-form*, the molecules of minerals in most cases have the property of so arranging themselves during growth as to produce structures having not only definite physical properties but also characterized by geometric shapes; and such structures are known as crystals. Each mineral has its particular crystal form which it endeavors to assume if not interfered with during its growth. Figures of some of these forms are shown in the description of the minerals which follows. They are not commonly well developed in the crystal grains which make the rock particles on account of mutual interference during their growth.

Cleavage is the property possessed by many minerals of splitting or breaking more or less perfectly in certain directions through the crystal, and yielding smooth flat surfaces. A familiar example is mica, whose usefulness depends on its perfect cleavage. It varies greatly in different minerals, some, like quartz, being destitute of it.

The *color* of minerals is an almost obvious property; the color in powdered form may be quite different from the mineral in mass and is most easily seen in the *streak*, which is produced when a bit of the substance is drawn across an unglazed porcelain plate.

Minerals vary much in their *hardness*; thus gypsum may be scratched by the finger nail, while the diamond is not scratched by any other substance. Simple means of testing hardness may be found in the knife-point, a bit of feldspar, or one of quartz, each being successively harder than the former.

List and Description of Rock-minerals

Albite, see under Feldspar.

Amphibole, see under Hornblende.

Anorthite, see under Feldspar.

Apatite. — Occurs in hexagonal prisms, with ends rounded or capped by six-sided pyramids, greenish or brownish in color; is easily scratched by a knife; has no good cleavage. It is a phosphate of lime, with fluorine $(CaF)Ca_4(PO_4)_3$, and although sometimes found in large crystals it occurs chiefly in excessively

minute microscopic ones distributed through many kinds of rocks. While of no great geological importance it fulfills an important function in furnishing to the soil, when the latter is made by rock decay, the phosphorus so necessary to plant-life and (through the plants) to animals for their bony structures, etc.

Aragonite. — Calcium carbonate, $CaCO_3$, like calcite, but differs from the latter in its crystallization, which is orthorhombic. Lacks the cleavage of calcite, which readily distinguishes it. Colorless, white, or tinted. While it sometimes occurs as a vein mineral its chief geological interest is in the fact that it is the form of calcium carbonate which is chiefly deposited by organic life; thus it is a common component of many shells, especially in the pearly layers.

Augite, see under Pyroxene.

Biotite, see under Mica.

Calcite, carbonate of lime, $CaCO_3$. One of the most important of geological minerals. Often occurs in crystals, either pointed pyramidal, or prismatic, or flattened rhombohedral in shape; generally whitish in color, or clear transparent; sometimes tinted. Is often massive, filling fissures, or in grains, as in marble. Three directions of excellent cleavage not at right angles, forming rhombs. Easily scratched with a knife; effervesces readily in cold acid. Besides occurring with the properties mentioned, as filling veins and cavities and forming marble, calcite in the form of minute, not distinctly crystallized granules constitutes the cementing substance of the grains of various rocks, such as many sandstones; and in the limestones, chalks, etc., makes up the entire mass of the rock, or nearly so.

Chert, see under flint.

Chlorite. — This is used as a general name for a group of minerals whose exact chemical nature is not yet well known. They are hydrous silicates of aluminum, containing ferrous iron and magnesium. In outward properties chlorite is green to dark green in color, and like mica it has one very perfect cleavage, but unlike it the cleavage leaves although tough are not elastic. Although sometimes occurring in crystals which are flat six-sided tablets it is usually seen in scaly aggregates, which, although sometimes coarse, are more apt to be fine, producing massive forms. Chlorite is a secondary mineral and is formed by the alteration and decay of other minerals containing iron, magnesia and alumina, such as hornblende, pyroxene, and mica, in previously existent rocks. The dark green color of many igneous rocks is due to its formation in them; thus the dull green appearance, and more or less soft, earthy character of many traps and basalts is largely produced by the change of some of the original minerals into this substance. It is also of common occurrence in the metamorphic rocks; which, as in green slates, owe their

color to finely disseminated particles of it; while in chlorite-schist it is a prominent ingredient.

Clay, Kaolin. — Under the heading of clay several different substances are included, compounds of silica, alumina, and water. The most important of these is *Kaolin* which may be taken as the basis of true clay. Its chemical formula is $H_4Al_2Si_2O_9 = Al_2O_3 \cdot 2\,SiO_2 \cdot 2\,H_2O$. It consists of excessively minute thin platy or scaly crystals aggregated in masses. Soft; when wet coherent, forming a plastic mass, which dries coherent. Naturally white in color, but often tinted red or yellow by iron oxides, or gray to black by organic matter. On rubbing between the fingers kaolin has a smooth, greasy feel; a dry piece usually adheres to the tongue; when dry and breathed upon it has a peculiar odor, and this helps to detect its presence. Chiefly formed by the decay of feldspar. An important constituent of various rocks and soils.

Dolomite. — This word is used in two ways: mineralogically, as the name of a mineral, and geologically, as the name of a rock, largely or wholly composed of it. The mineral dolomite is a compound of one molecule of carbonate of lime with one molecule of carbonate of magnesia $CaCO_3 \cdot MgCO_3$. Its general physical properties of crystallization, color, hardness, etc., are so like those of calcite (page 407) that it is not easily distinguished from it. The best test is by chemical means; calcite effervesces freely in any weak acid when *cold;* to produce this with dolomite the acid must be *hot.* A further chemical test for magnesia in the solution after eliminating the lime is confirmatory. Many limestones and marbles are in part composed of dolomite, and may pass into dolomite in the geological sense. The origin of dolomite has been discussed on page 181.

Epidote. — This mineral is a complex silicate, containing variable amounts of alumina, iron and lime with some hydrogen. It may be considered a mixture, in varying proportions, of $Ca_2(AlOH)Al_2(SiO_4)_3$ and $Ca_2(FeOH)Fe_2(SiO_4)_3$. It often occurs in prismatic or bladed crystals with one perfect cleavage, or in grains, sometimes aggregated into masses. The color is green, from light to dark, and usually of a yellowish-oily tone. Too hard to be scratched with a knife. Epidote is a product of alteration of other mineral substances and is produced in regional or contact metamorphism, especially when impure stratified rocks containing calcareous matter, sand, clay, limonite, etc., are subjected to such processes.

Feldspar. — These are, perhaps, the most important of all minerals from the geological standpoint since the bulk of the rocks forming the continental masses appears to be most largely composed of them. They are silicates of alumina with lime, soda, or potash and accord-

ingly as one of these three is present different kinds of feldspar are recognized and named, as follows:

(*a*) *Orthoclase*, $KAlSi_3O_8$, silicate of potash and alumina.
(*b*) *Albite*, $NaAlSi_3O_8$, silicate of soda and alumina.
(*c*) *Anorthite*, $CaAl_2Si_2O_8$, silicate of lime and alumina.

Pure varieties of feldspar, of the compositions indicated above, are mostly confined to crystals found in veins and druses in the rocks; they sometimes occur as component particles of the rocks themselves, but are rare; in most cases the rock grains are mixtures of either orthoclase and albite on the one hand, or of albite and anorthite on the other, and are then known as:

(*d*) *Alkalic feldspar*, $(KNa)AlSi_3O_8$, mixtures of *a* and *b*.
(*e*) *Plagioclase feldspar* $(NaAlSi_3O_8)_x + (CaAl_2Si_2O_8)_y$, mixtures of *b* and *c*.

In (*d*), alkalic feldspar, the potash compound is usually in considerable excess and it is apt to be referred to as orthoclase, although not pure. In the plagioclase group all transitions from pure albite at one end to anorthite at the other are known; one mixture in which the two are about equal is called *labradorite*.

In physical properties the different kinds of feldspar are much alike. The outward crystal form is not a matter of much impor-

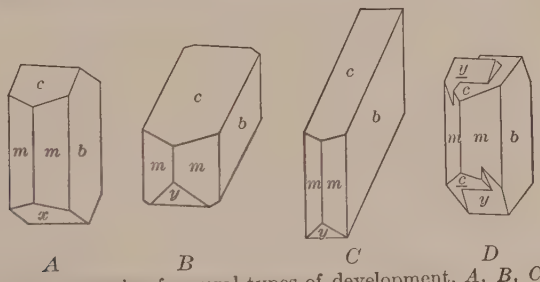


Fig. M_1. — Feldspar crystals of several types of development, *A*, *B*, *C*, *D*. In *D* a twin crystal (Carlsbad type) is seen.

tance, as it is rarely seen in rocks, except in the phenocrysts or large embedded crystals of porphyries (see page 307). In them the crystals usually have the shapes shown in *A*, *B*, *C*, and *D* of the adjoining Fig. M_1, and the outlines seen on a broken rock surface are various sections of these crystal forms. In Fig. M_1, *D*, two crystals are seen intergrown in what is known as a twin crystal; these may often also be observed in the rocks.

Feldspars possess two directions of excellent cleavage, one parallel to the face *b* of the crystals, the other parallel to *c*; these are at right angles to each other (orthoclase), or very nearly so (plagio-

clase). These cleavages give the broken surfaces of the grains seen in rocks minutely terraced or step-like appearances, whose levels in a single grain reflect light simultaneously. This is an important means of distinguishing feldspar particles from quartz grains in the rocks, the latter having no cleavage.

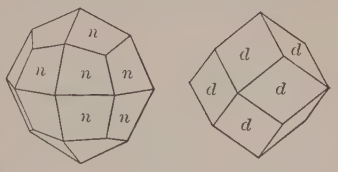
In color, the feldspars are usually white, pinkish to deep flesh-red, grayish, or yellowish, very rarely limpid and colorless, and of a porcelain-like appearance. Orthoclase is very often pink or red, plagioclase white, grayish, or yellow; this rule is by no means, however, an invariable one. A better means of distinguishing them, if it can be seen, especially by aid of a lens, is that one of the cleavage surfaces of plagioclases is often ruled by excessively fine parallel lines; this does not occur in orthoclase on account of its having a different crystallization from plagioclase. The feldspars are hard and cannot be scratched with a knife-point, but may be scratched with quartz; they are not acted upon by ordinary acids, properties which serve to distinguish them from some other cleavable rock minerals, such as calcite and dolomite.

Under ordinary processes of weathering the feldspars are chiefly changed into clay (kaolin); they may often be seen in the rocks more or less altered. They then become soft and yield the clay odor. In regional metamorphism, especially when combined with hydrothermal actions, they are converted into white mica, sericite, and take part in the formation of a variety of other secondary minerals.

Flint. — This is not a rock in the sense that it occurs in extensive independent formations, like limestone, nor is it a definite mineral, like calcite. It may, however, be considered conveniently here among the minerals. It is an intimate microscopic mixture of crystallized silica, SiO_2 (quartz), and non-crystalline silica containing some combined water (opal). Its color is dark gray, or black, from organic matter; its hardness is well known and like that of quartz; it cannot be scratched by the knife or by feldspar. It has no cleavage but a conchoidal fracture. Its use for striking fire and in furnishing the weapons and tools of primitive man are well known. Its occurrence in concretions and masses in chalks and limestones (in the latter often called *chert*) has been alluded to in this book (page 274). Somewhat similar masses of silica, more or less pure, sometimes white or light gray, and often differently colored by iron (yellow, red, or brown) and other substances, in some cases of similar but often of different or uncertain origin, have been variously termed *jasper*, *jaspilite*, *hornstone*, *novaculite*, etc. In places, like the jaspilites of the Lake Superior region, or the novaculites of Arkansas, they may form beds of considerable importance.

Garnet. — This is the name of a group of minerals which have the common chemical formula $X_3Y_2(SiO_4)_3$, and are thus salts of orthosilicic acid, H_4SiO_4; X is either calcium, magnesium, or ferrous

iron, or mixtures of them (bivalent elements); Y is either aluminum, ferric iron, or chromium, or mixtures of them (trivalent elements). The pure compounds have received definite names, thus $Fe_3Al_2(SiO_4)_3$ is known as *almandite* and for the most part composes the *common garnet* ordinarily seen in rocks. Garnets crystallize in the forms shown in Fig. M_2, A and B, and crystals of these forms are often seen in the rocks, especially in the mica-schists. The type A, when poorly developed, often appears as a spherical object embedded in the rocks.



A *B*

Fig. M_2. — Garnet crystals.

The mineral has no good cleavage, is very hard so that it cannot be scratched by a knife or by feldspar, and varies greatly in its colors; common garnet is deep red to brownish-red and sometimes black; yellow and brown tones are also common in garnets containing lime.

Garnets are found chiefly in metamorphic rocks; in gneisses and crystalline schists. Lime garnets $Ca_3Al_3(SiO_4)_3$ (*grossularite*) occur mostly in calcareous rocks, such as impure limestones which have been metamorphosed by the action of intruded igneous masses.

Gypsum. — This mineral, called also *selenite*, is the sulphate of lime with water, $CaSO_4 \cdot 2\,H_2O$. It is sometimes found in good crystals, of more or less tabular lozenge-shaped forms, but as a rock constituent it is massive, foliated with curved surfaces, or granular to compact, and less commonly fibrous. The crystals and large crystal grains have one perfect cleavage by which it may be split into thin sheets. The normal color is white or colorless, but it is often tinted reddish, yellowish, or even black by impurities. It is a soft mineral and may be readily scratched by the finger nail.

Gypsum rock is widely distributed in the stratified formations, in the form of extensive beds, often of great thickness and is especially found with limestones and shales. It is indicative of arid conditions prevailing at its time of formation. Its use in making plaster of Paris is well known; this is done by heating it until a portion of the water is driven from the molecule; on mixing with more water it is at first plastic, when the water has again been taken up it becomes hard.

Halite, see Rock-salt.

Hematite. — Red oxide of iron or ferric oxide, Fe_2O_3. This substance is found in several forms, one of which is crystalline with a steel-like luster, but the most important one geologically is known as common red hematite. In this condition it is not crystallized,

but is massive, granular to compact, often in rounded forms, sometimes earthy. It has no metallic luster, is opaque and of a dark red to brown color; its powder and streak are red (distinction from limonite). It occurs in sedimentary and metamorphic rocks in beds and masses, sometimes of great size, and furnishes a valuable ore of iron. It is also common as a cement of the grains of some stratified rocks, such as red sandstones, and as a coloring matter it is widely distributed in all kinds of rocks and soils, in some cases perhaps as hydro-hematite, $2\,Fe_2O_3 \cdot H_2O$.

In the crystalline form, as dark metallic looking specks, it is widely distributed in igneous rocks and certain crystalline schists, but may be confused with magnetite, which see. The pure mineral contains 70.0 per cent of iron.

Hornblende. — The name *amphibole* is used interchangeably with hornblende and is given to an important group of rock-forming minerals, which are chemically salts of metasilicic acid, H_2SiO_3, in which the hydrogen has been replaced by various metals, such as calcium, magnesium, or ferrous iron, or by mixtures of them, and by various radicals. The composition is too complex to be represented very simply, but one variety (actinolite) is very nearly $Ca(MgFe)_3(SiO_3)_4$; *common hornblende* contains also alumina and ferric iron.

Hornblendes usually crystallize in prismatic forms; the crystals are apt to be long and bladed, sometimes, as in some hornblende-schists, they may be very fine and needle-like; in some cases, as in certain porphyries, the prisms may be short and stout, Fig. M_3, *A*, or again the mineral may occur in irregular grains and masses, as in many diorites. In the igneous rocks the color is usually black to greenish-black; in the metamorphic rocks various shades of green to black, less commonly pale, or even whitish.

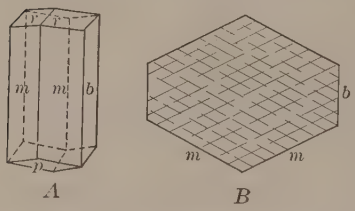


Fig. M_3. — *A*, Hornblende crystal; *B*, section of crystal at right angles to vertical axis of prism showing angles of prismatic cleavage.

Hornblende is rather hard but all varieties may be scratched with quartz, some by a knife point. It has a highly perfect cleavage parallel to the prism faces, and the two directions of cleavage along the prisms meet at angles of 125° and 55°, Fig. M_3, *B*, a fact of importance in helping to distinguish it from pyroxene (see pyroxene). The glittering prismatic faces seen on the blades and needles of the mineral on a fractured rock surface are mostly due to this cleavage. In small grains it is difficult to distinguish from pyroxene.

Hornblende under proper conditions may be changed into serpentine, chlorite, carbonates, etc., and by continued weathering into limonite, carbonates, and quartz.

The hornblendes are important geological minerals and occur in a great variety of igneous and metamorphic rocks. They may be present in only a few scattered crystals, or to such an extent that the rock, as in hornblende-schist, is mainly composed of them.

Iron Ores. — These are chiefly *hematite*, *magnetite*, *limonite*, and *siderite* and information concerning them will be found under these headings.

Kaolin. — This is the basis of clay; see under *clay*.

Labradorite, a feldspar consisting of about equal mixtures of albite (soda-feldspar) and anorthite (lime-feldspar). Named from the coast of Labrador where it occurs in large crystals, often showing a play of colors. See Feldspar.

Limonite. — Yellow oxide of iron, $2\,Fe_2O_3 \cdot 3\,H_2O$, partly hydrated ferric oxide. Does not crystallize, but is found in earthy formless masses, which are sometimes compact and of rounded shapes, or stalactite-like, and may exhibit a radiating structure. There is no cleavage and the mineral, while usually dull or earthy in appearance, may in the compact globular forms show a silky, or even somewhat metallic luster. Color is usually brown, from light to dark, or brownish-yellow. The powder, or streak, is yellow-brown, which serves to distinguish it from hematite. Per cent of iron 59.8.

Limonite is found in several ways, but is always a secondary mineral, that is, one formed at the expense of previously existent ones by weathering and other agencies which act chemically upon them. In altered igneous and metamorphic rocks it may be seen as small earthy masses resulting from the decay of some previous iron-bearing mineral. It occurs in the sedimentary strata, see page 393, as masses and beds in compact, globular, or concretionary forms. As bog-iron ore it is loose, porous, and earthy. Finally, it forms the yellow coloring matter of many soils, clays, and sedimentary rocks. It is a valuable ore of iron.

Magnetite. — Ferrous-ferric oxide, $FeO \cdot Fe_2O_3$, (Fe_3O_4). Crystallizes in octahedrons, sometimes in dodecahedrons like Fig. M_2,B, page 411, but is usually seen in small grains in the rocks whose forms are irregular; sometimes in larger masses. Has no cleavage, is brittle and usually too hard to be scratched by a knife. Has a metallic luster, sometimes dull; is opaque and resembles bits of iron or steel in the rocks. Its property of being attracted by a magnet helps to distinguish it from other somewhat similar looking minerals.

Its powder or streak is black. Is widely distributed in igneous and some metamorphic rocks, usually in small grains but sometimes in larger masses, especially in contact metamorphic rocks, and is then a valuable ore of iron. Per cent of iron, 72.4.

Micas. — The micas are a group of rock minerals which are characterized by a remarkably perfect cleavage in one direction, by means of which they may be split into almost indefinitely thin, flexible, elastic leaves. They are silicates of complex composition and for practical purposes may be divided into two groups, *light* colored micas, of which *muscovite* may be taken as an example, and *dark* micas, or *biotite*, and related kinds. Muscovite, beside the silica, contains alumina, potash, and hydrogen; biotite contains in addition magnesia and iron. Their simpler formulas may be shown chemically as follows:

$$\text{Muscovite} = H_2KAl_3(SiO_4)_3.$$

$$\text{Biotite} = (HK)_2(MgFe)_2(AlFe)_2(SiO_4)_3.$$

They crystallize in six-sided (sometimes four-sided) tables, whose faces are nearly always rough, while the flat bases are formed by the glittering cleavage surfaces, Fig. M_4. They are also often seen in rocks in flakes, scales, or shreds, sometimes curled or bent, with shining cleavage faces. *Muscovite* is colorless to white, pale brown, or greenish; thin leaves are transparent. The huge crystals of it found in granite-pegmatite veins furnish the mica which is ordinarily used commercially. In very minute scales in the rocks it has a silky appearance and is known as *sericite*. *Biotite* is black and only translucent in thin scales. All micas are easily scratched with a knife; they are readily distinguished from chlorite and talc by the elasticity of the cleavage plates, and this and the cleavage distinguishes them from other rock minerals.

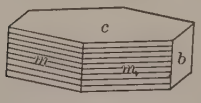


Fig. M_4. — Crystal of mica, showing cleavage parallel to base, *c*.

Biotite is found chiefly in igneous rocks, especially in granites, syenites, some diorites, in certain felsite lavas and porphyries, and in some trap-like rocks occurring in dikes. Muscovite occurs in pegmatite veins, but is especially found in the metamorphic rocks, as in gneisses, and is common in many crystalline schists; thus in mica-schist it plays the chief rôle. Under certain conditions, by the action of heated vapors and water, feldspars are converted into muscovite, especially the sericite variety.

Muscovite, see micas, above.

Ocher. — This name is given to clays colored deeply red or yellow by oxides of iron (hematite or limonite); thus red ocher, yellow ocher.

Olivine. — Silicate of magnesia, Mg_2SiO_4, the magnesia more or less replaced by ferrous iron. Crystals are rarely well developed in rocks; commonly it appears in grains or small granular masses. Color olive to yellow-green; bottle-green very common; transparent to translucent, often turns reddish and opaque by oxidation of the iron. Hard, cannot be scratched with knife-point; glassy luster.

Olivine, often called chrysolite, occurs almost entirely in ferromagnesian igneous rocks, as in gabbros, peridotites, dolerites and basalts. It is often seen in the basalts scattered in small bottle-green grains. A variety of peridotite composed of almost pure olivine occurs in several regions and is known as *dunite*. The mineral alters readily to serpentine and is probably the chief source of this substance.

Orthoclase. — See Feldspar.

Plagioclase. — See Feldspar.

Pyroxene. — This is an important group of minerals which, like the hornblendes, are salts of metasilicic acid, H_3SiO_3, in which the hydrogen has been replaced by magnesium, calcium, and iron, or by mixtures of them, and in some cases by sodium, or various radicals. As ordinarily seen in the rocks the light-colored pyroxenes are mostly *diopside*, $CaMg(SiO_3)_2$, with little or no iron, while the dark or black kinds, commonly seen in igneous rocks, are apt to be the variety known as *augite*. Other varieties, such as *hypersthene* $(MgFe)SiO_3$, also occur, but are of less importance.

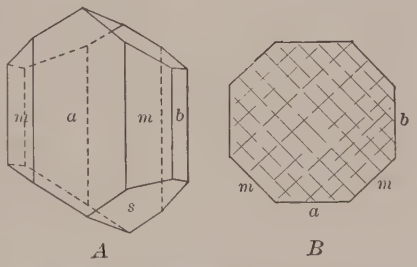


Fig. M_5. — *A*, augite crystal. *B*, section normal to vertical axis, showing prismatic cleavage.

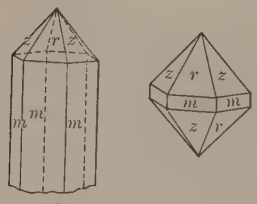
All pyroxenes have the common property that they form prismatic crystals with a double cleavage parallel to the main prism faces, which intersect at nearly right angles (93° and 87°). The crystals are apt to be short and stout, and well-formed examples of augite are often found in basaltic porphyries and lavas, see Fig. M_5, *A* and *B*. Pyroxenes are also found in grains and more or less shapeless masses, as is common in gabbros and dolerites.

Pyroxenes, while sometimes white, or even colorless (pure diopside), are usually colored more or less greenish, light to dark, while augite is black and opaque. Some can be just scratched by a knife-

point, all are scratched by quartz. The luster, which is often wanting, is glassy.

Pyroxenes resemble hornblendes in the rocks and are frequently difficult or even impossible to distinguish from them. The slender-bladed forms, and excellent glittering cleavage of hornblende often aid in discriminating it from pyroxene whose cleavage is not so good, and whose crystals are apt to be shorter and stouter. A comparison of the angle at which the cleavages meet (pyroxene 93°, 87° and hornblende 55°, 125°, compare Figs. M_3 and M_5) also helps to distinguish them. But it is often impossible, as in dolerites, to discriminate between them by simple observation and without other methods of testing. Pyroxenes are very important minerals in the igneous rocks, especially in the dark-colored ferromagnesian kinds, such as gabbros, dolerites, and basalts, which are largely composed of the augite variety. In the feldspathic rocks, such as syenite and certain felsite lavas, they sometimes occur, but are of less importance. While they are found in some metamorphic rocks they are of far less importance in this class than the hornblendes. Indeed by metamorphic action pyroxene is generally converted into hornblende, and much of the latter in the schists owes its origin to such conversion of pyroxene, when previous igneous rocks have been changed into them.

Quartz, pure silica, SiO_2. Crystallizes in hexagonal prisms capped by a six-sided pyramid. This is the common form in veins, druses, geodes, and other cavities in rocks, Fig. M_6,*A*. In embedded phenocrysts in porphyries the prism is apt to be small or wanting, see Fig. M_6,*B*, the form is poorly developed and the crystal has usually a roughly spherical shape. In general it has no outward crystal form but, as in igneous rocks such as granite, it is in small shapeless masses. In quartz veins it may be massive; in sandstones it is in cemented rounded grains, and these in quartzites may be so firmly cemented as to form practically massive quartz.



A *B*

Fig. M_6. — Quartz crystals.

Quartz has no cleavage, but a conchoidal fracture which helps to distinguish it from feldspar in many rocks. In color the well-formed crystals of veins are usually colorless, or smoky-brown, sometimes purple, but the rock-making quartz is generally white, smoky, to brown, rarely black; massive quartz of veins is usually white. The luster is glassy to greasy; the mineral is hard and cannot be scratched by a knife but scratches glass and feldspar.

It is one of the commonest of minerals and occurs in igneous, sedimentary, and metamorphic rocks. With feldspar it composes more or less entirely the bulk of granites, many felsites, and is found in some diorites. Occurs also in gneisses and many schists. In pure sandstones and quartzites it may be almost the only mineral present. Excepting limestones, chalks, and marbles, and the dark heavy igneous rocks, like dolerite and basalt, its presence in rocks should, at least, be always suspected. It is not acted upon by the ordinary agents which decompose other rock minerals and this accounts in part for its wide distribution, and also its being so commonly one of the constituents of soils.

Rock-salt, halite, sodium chloride, NaCl. Easily recognized by its cubic crystals, good cubic cleavage, ready solubility and saline taste. Colorless and transparent to white, translucent, sometimes tinted. Common salt is the only chloride in nature which is of wide geological importance. In addition to its occurrence in the sea it forms beds, sometimes enormously thick, in the sedimentary formations, usually in clays and shales, and is generally accompanied by gypsum. Its presence is thus indicative of arid conditions at the time of its deposition.

Serpentine. — Hydrated silicate of magnesia, $H_4Mg_3Si_2O_9$ ($2\,H_2O \cdot 3\,MgO \cdot 2\,SiO_2$). This mineral does not crystallize but is generally found massive, sometimes granular and not infrequently fibrous, with fine, silky, flexible, and easily separated fibers. The color is usually green from light to dark and more or less yellowish or olive in tone; sometimes nearly black. Fibrous varieties white to brown, often pale brownish. Luster greasy, wax-like; has a greasy feel; soft, readily scratched or cut by a knife; translucent to opaque.

Serpentine is a secondary mineral resulting from the alteration of previously existent magnesia-bearing silicates, such as hornblende, pyroxene, and especially olivine. It appears to be formed by the action of heated waters on igneous and metamorphic rocks and is found as masses and layers, sometimes associated with igneous, often with other metamorphic rocks. The fibrous variety, called also *chrysotile*, usually occurs in seams, in massive serpentine. Greenish and yellowish serpentines are frequently cut and used as ornamental stones in decoration and building.

Siderite; ferrous carbonate, $FeCO_3$. Carbonate of iron, when a pure mineral, is extremely like calcite and dolomite, whose properties should be consulted. It crystallizes in a similar form, has the same rhombohedral cleavage, and like them is soft and attacked by acids with effervescence; apt to be brownish in color. The crystallized mineral is not of great geological or economic importance, but massive siderite, either compact or granular in character, is a valuable iron ore. Beds of it, more or less impure with admixed clay and limonite, have

a wide distribution and are known as *clay-iron-stone*. A variety colored black by coaly matter is known as *black-band* ore. In many places these deposits are of great technical value. Per cent of iron in the pure mineral, 48.21.

Talc. — This mineral, like serpentine, is a secondary silicate of magnesia, $H_2Mg_3(SiO_3)_4 = H_2O \cdot 3\,MgO \cdot 4\,SiO_2$, produced by the action of circulating heated fluids on previously existent silicates, such as hornblendes, pyroxenes, and olivine. What the conditions are which determine its formation, rather than that of serpentine, are not known. The two are sometimes found associated.

It is usually seen in compact or strongly foliated masses, sometimes in scaly aggregates. Has a perfect cleavage in one direction like mica, but the cleavage leaves, though flexible, are not elastic. Has a mother-of-pearl luster and a soft greasy feel. Softer than chlorite, marks dark cloth with a white streak. Color white to greenish or gray; usually translucent.

Talc is only important in the metamorphic rocks where it occurs in talc schist and in the more massive rock known as *steatite* or *soapstone;* in the latter it is usually more or less mixed with chlorite.

Minerals Important as Ores

Introductory. — There are certain minerals which are not of importance in a broad geological sense, because they occur in such small amounts in the earth's crust, but are yet of great importance to man on account of the fact that they are the chief sources of supply for the metals used in commerce and the arts. Gold is a good example of this, its value as a medium of exchange depending for the most part on its rarity.

The ores of iron stand in an intermediate position, for they are not only important technically, but also as rock-minerals, as previously shown. The metals which are of most importance and whose chief ores are described are *gold*, *silver*, *lead*, *copper*, and *iron*.

Gold

This metal occurs in nature chiefly in the native state, as metallic gold. Its properties are too well known to need further mention, but it may be added that it is easily distinguished from other substances that may resemble it in color, such as iron-pyrites, by its softness and malleability, as it is rather easily cut by the knife and may be hammered out into thin plates.

Silver

This metal occurs as native metallic silver and combined with sulphur and also arsenic in several minerals. An occurrence, imperceptible to the eye, but of great importance, is that lead and sometimes copper ores are frequently enriched by its presence; it is extracted during the process of metallurgical treatment to which they are subjected to obtain the metals.

Native Silver. — Is distinguished by its color, softness and malleability, in which it resembles gold.

Argentite, Ag_2S, silver sulphide, is perhaps the most common form in which silver occurs in combination. It is usually massive, sometimes in crystal groups, has a shining metallic luster on a fresh surface but commonly appears black and dull. It can be easily cut, like lead, with a knife and is very heavy. On fusing it the sulphur burns off leaving pure silver behind. Percentage of silver 87.1.

Lead

Galena, PbS, lead sulphide, is one of the most common ores of lead. In color it resembles lead, but is brittle and breaks with a perfect cubic cleavage. It is usually crystallized in cubic forms or is in cleavable masses. It is very heavy and easily fusible. Percentage of lead 86.6.

Cerussite, $PbCO_3$, lead carbonate. Occurs in white or colorless crystals, or in granular whitish crystalline masses. Crystals have a very high luster. It is very heavy for a non-metallic appearing mineral. It is easily fusible, yielding lead and lead-oxide; dissolves in warm dilute nitric acid with effervescence, and a little sulphuric acid produces a precipitate of white lead sulphate in the solution. Percentage of lead 77.5.

Anglesite, $PbSO_4$, lead sulphate. Generally in whitish masses, granular to compact, but also occurs in white to colorless crystals. The massive varieties are dull to earthy in appearance, but the crystals have a high luster and are cleavable. Like cerussite unusually heavy, but easily distinguished from it by the lack of effervescence when treated with nitric acid. Fuses easily. Is often found associated with galena, as an alteration product of it. Percentage of lead 68.2.

Copper

Native copper, the metal sometimes occurs as an ore, especially in the Lake Superior region; its properties need no further description.

Cuprite, Cu_2O, copper oxide, or ruby copper as it is often called, usually occurs in massive form but sometimes in crystals showing the form of the cube or octahedron. It has a high luster in the crystals to sub-metallic or dull when massive. The color is red and in clear crystals ruby-like. Easily fusible, tingeing the blowpipe flame green; is also very heavy. Percentage of copper 88.8.

Chalcopyrite, $CuFeS_2$, copper pyrites. This is one of the most important ores of copper. It commonly occurs in compact, massive form and has a brass yellow color and metallic appearance; it is often tarnished. It resembles common iron pyrites, FeS_2, but is easily distinguished from it by its softness as it can be easily scratched with a knife. Is moderately heavy. Percentage of copper 34.5.

Chalcocite, Cu_2S, copper glance. Generally found massive, crystals rare. Has a conchoidal fracture, a metallic luster, color of lead and shining on fresh surface but often tarnished and black; is heavy and has a black streak or powder. Fuses easily; dissolves in nitric acid and solution gives the blue color of copper with ammonia; is soft and easily scratched with a knife. Common in the secondary enrichment zones of veins containing copper. Percentage of copper 79.8.

Malachite, $Cu(OH)_2CO_3$, green carbonate of copper. Occurs in crusts or rounded masses, often with a velvety surface, of a bright green color of varying shades, and with a fibrous, radiating structure. Usually dull in luster and opaque. Soft, easily scratched with a knife. Dissolves in acid with effervescence. Percentage of copper 57.4.

Azurite, $2\,CuCO_3 \cdot Cu(OH)_2$, blue carbonate of copper. Often in distinctly grouped crystals, also in rounded radiating masses. Of a deep azure blue color. Crystals with glassy luster and often transparent; soft, easily scratched with a knife. Like malachite dissolves in acid with effervescence. Percentage of copper 55.3.

Iron

The ores of iron, hematite, limonite, magnetite and siderite have been already described under the preceding group of rock-minerals. A remaining iron mineral of importance is pyrite.

Pyrite, FeS_2, iron pyrites. Commonly seen in crystals, of a cubic, or related form; crystals often striated on the faces; also occurs massive. Of a brass yellow color, sometimes tarnished; of a high metallic luster and opaque. Very hard, cannot be scratched with a knife, which distinguishes it from chalcopyrite. Its hardness and brittleness distinguish it from gold, for which it is sometimes mistaken. It is not used as an ore of iron, but is sometimes mined for sulphur.

Gangue Minerals

Common gangue minerals associated with ores are *quartz*, *calcite*, *dolomite*, *siderite* and *pyrite*, previously described in this appendix. In addition two other rather common gangue minerals may be mentioned, *barite* and *fluorite*.

Barite, $BaSO_4$, barium sulphate, commonly called "heavy spar." Generally in divergent groups of tabular crystals, also massive, coarsely cleavable or granular. Has perfect cleavages. Generally light colored, whitish, bluish, or reddish brown, crystals sometimes transparent; luster glassy or pearly. Heavy for a non-metallic mineral. Insoluble in acids and does not effervesce. Characterized by its good cleavage, light color and heaviness.

Fluorite, CaF_2, fluoride of calcium; fluor-spar. Usually in cubic crystals, but also massive and coarse to fine granular. Color generally light green or purple, rarely white, bluish, etc., commonly transparent to translucent and of glassy luster. Has a perfect cleavage in four directions by which it may be cleaved into octahedrons. Easily scratched with a knife; not a heavy mineral like barite. Does not effervesce with acids, which distinguishes it from carbonates (calcite, etc.).

APPENDIX B

TECHNICAL NAMES OF THE FOSSILS ILLUSTRATED

As Historical Geology is replete with technical names of plants and animals which do not interest the undergraduate student and are of value only to the specialist, it was decided to keep them out of the main part of the book, except in the case of certain of the striking extinct organisms that have no counterpart in the living world. The teacher, however, will want to know the names of all the fossils illustrated so that he may connect his wider knowledge with the figures, and therefore the scientific names of the forms pictured in the various plates and figures are given in this appendix. Unless otherwise indicated, the figures are natural size.

Plate 1, Page 593

Fig. 1, *Holmia bröggeri*, × $\frac{1}{3}$; 2, *Olenellus thompsoni*, × $\frac{1}{2}$; 3, *Atops trilineatus;* 4, *Eodiscus speciosus;* 5, *Archæocyathus rensselæricus*, × 3; 6, *A. profundus;* 7, *Paterina bella*, × 4; 8 and 9, *Obolella crassa*, × 3; 10 and 11, *Stenotheca rugosa;* 12, *S. rugosa abrupta.*

All after Walcott.

Plate 2, Page 595

Middle Cambrian:

Fig. 1, *Paradoxides harlani*, × $\frac{1}{4}$; 2, *Dorypyge curticei*, × $\frac{1}{2}$; 3, *Ptychoparia kingi*, × $\frac{3}{4}$; 4, *Agnostus montis*, × 3.

Upper Cambrian:

Fig. 5, *Crepicephalus texanus*, × $\frac{1}{2}$; 6 and 7, *Owenella antiquata*, × 2; 8, *Hyolithes primordialis;* 9–11, *Billingsella coloradoensis*, × 2; 12 and 13, *Huenella texana*, × $1\frac{1}{2}$; 14, *Lingulepis acuminata*, × 2.

Mostly after Walcott.

Plate 4, Page 624

Figs. 1 and 2, *Phyllograptus ilicifolius* and *P. angustifolius*, crushed flat; 3, *P. angustifolius*, about × 2, uncrushed; 4, *Tetragraptus fruticosus;* 5, *Goniograptus postremus*, × $\frac{1}{2}$; 6, fragment of *Loganograptus logani;* 7, *Climacograptus bicornis;* 8, *Diplograptus ruedemanni*, × $\frac{3}{4}$; 9 and 10, *Orthis tricenaria*, × $\frac{3}{4}$; 11–13, *Dalmanella testudinaria;* 14–16, *Hebertella sinuata*, × $\frac{1}{2}$; 17, *Dinorthis subquadrata*, × $\frac{3}{4}$; 18 and 19, *Platystrophia laticosta*, × $\frac{3}{4}$; 20 and 21, *Rafinesquina alternata*, × $\frac{3}{4}$; 22, *Strophomena planumbona*, × $\frac{1}{2}$; 23 and 24, *Triplecia extans*, × $\frac{1}{2}$; 25, *Leptæna rhomboidalis*, × $\frac{3}{4}$; 26, *Plectambonites sericeus;* 27–29, *Rhynchotrema capax*, × $\frac{3}{4}$.

In the main from the New York, Ohio, and Indiana State Surveys.

Plate 5, Page 626

Fig. 1, *Modiolopsis modiolaris*, × ⅔; 2, *Pholadomorpha divaricata*, × ⅔; 3, *Colpomya constricta;* 4, *Cyrtodonta huronensis*, × ½; 5, *Pterinea demissa*, × ½; 6, *Opisthoptera fissicosta*, × ½; 7, *Byssonychia radiata*, × ⅓; 8, *Ctenodonta cingulata*, × 2; 9, *Protowarthia cancellata*, × ½; 10, *Cyrtolites ornatus*, × ½; 11, *Trochonema umbilicatum*, × ½; 12, *Eotomaria supracingulata*, × ½; 13, *Cyclonema humerosum*, × ⅔; 14, *Helicotoma planulatoides;* 15, *Maclurea logani* with the operculum, × ½; 16, *Hormotoma gracilis*, × ½; 17, *Orthoceras multicameratum*, × ⅛; 18, *Cyrtoceras juvenale*, × ½; 19, *Schroederoceras eatoni*, × ⅓; 20, *Eurystomites occidentalis*, × ¼.

In the main from the Ohio, New York, and Minnesota State Surveys. In part after Scott.

Plate 6, Page 628

Fig. 1, *Cyathospongia reticulata*, × ½; 2, *Zittelella typicalis*, × ½; 3 and 4, *Streptelasma profundum*, × ½; 5, *Glyptocrinus dyeri*, × ½; 6, *Ceraurus pleurexanthemus;* 7 and 8, *Calymene callicephala;* 9, *Basilicus canadensis*, × ⅔; 10, *Isotelus maximus*, × ½; 11, *Bumastus trentonensis*, × ½; 12, *Ampyx nasutus;* 13, *Trinucleus concentricus;* 14, protaspis stage of *Triarthrus becki*, × 20; 15, protaspis stage of *Proëtus parviusculus*, × 20.

In the main after the New York, Ohio, and Illinois State Surveys. Also after Beecher and Zittel.

Figure 381, Page 630

Fig. *A*, *Protospongia quebecensis; B*, *P. coronata; C*, *P. mononema; D*, *P. tetranema; E*, *P. cyathiformis.*

After Dawson and Hinde.

Plate 9, Page 667

Fig. 1, *Halysites catenulatus;* 2, *Favosites occidentalis*, × ¾; 3, *Troostocrinus reinwardti;* 4, *Eucalyptocrinus crassus*, × ½; 5 and 6, *Monomerella noveboracum*, × ½; 7, *Chonetes cornutus;* 8, *Pentamerus oblongus*, × ⅓; 9, *Rhynchotreta americana;* 10, *Spirifer crispus;* 11, *S. radiatus*, × ⅔; 12, *Hyattidina congesta;* 13, *Whitfieldella nitida*, × ½; 14, *Atrypa nodostriata;* 15, *Strophostylus cyclostomus*, × ⅔; 16, *Platyceras angulatum;* 17, *Diaphorostoma niagarense*, × ½; 18, *Ceratocephala dufrenoyi;* 19, *Staurocephalus murchisoni;* 20, *Deiphon forbesi;* 21, *Metopolichas breviceps*, × ½.

Mainly after the New York and Indiana State Surveys. Also from Scott and Zittel.

Plate 12, Page 675

Fig. 1, dorsal aspect of *Eurypterus remipes*, × ⅓; 2, same, from the ventral side, female, × ⅓; 3, *Hughmilleria socialis*, × ½; 4, *Eusarcus scorpionis*, × ⅓; 5, *Pterygotus buffaloensis*, × 1/25; 6, *Ceratiocaris.*

After Clarke and Ruedemann.

Plate 13, Page 681

Fig. 1, living American gar-pike, a ganoid (*Lepidosteus osseus*), × ⅙; 2, Devonian ganoid from Scotland (*Osteolepis macrolepidotus*), × ½; 3, Upper Devonian ganoid from Scaumenac Bay, Canada (*Scaumenacia curta*), × ½; 4, Devonian ganoid with cycloid scales, from Scotland (*Holoptychius flemingi*), × ½; 5, living

marine lamprey (*Petromyzon marinus*), $\times \frac{1}{6}$, note the seven openings back of the eye, exits from the gills; also edge of circular mouth, and absence of paired fins.

Figs. 2 and 4 after Woodward, British Museum Guide Book; Fig. 3 after Hussakof.

Plate 14, Page 683

Fig. 1, Lower Devonian acanthodian shark, from Scotland (*Climatius macnicoli*), $\times \frac{1}{3}$; 2, Upper Devonian shark, from Ohio (*Cladoselache fyleri*), $\times \frac{1}{5}$; 3, living Port Jackson cestraciont shark, from Australia (*Cestracion philippi*), $\times \frac{1}{10}$; 4, living lung-fish of Australia (*Neoceratodus forsteri*), $\times \frac{1}{12}$; 5, Devonian lung-fish, from Scotland (*Dipterus valenciennesi*), $\times \frac{1}{2}$.

Figs. 1 and 5 after Woodward, British Museum Guide Book; Fig. 2 after Dean; Fig. 3 after Garman.

Plate 16, Page 707

Fig. 1, *Pentremitidea filosa*, $\times 2$; 2, *Granatocrinus leda;* 3, *Elæacrinus verneuili;* 4, *Heliophyllum halli;* 5, *Cystiphyllum vesiculosum;* 6, *Phillipsastræa gigas;* 7, *Thamnoptychia limbata;* 8, *Syringopora perelegans;* 9, *Aviculopecten ornatus*, $\times \frac{2}{3}$; 10, *Pterinea flabellum*, $\times \frac{1}{2}$; 11, *Actinodesma erectum*, $\times \frac{2}{3}$; 12 and 13, *Nucula randalli;* 14, *Goniophora carinata*, $\times \frac{2}{3}$; 15, *Orthonota undulata*, $\times \frac{2}{3}$; 16, *Modiomorpha concentrica*, $\times \frac{1}{3}$; 17, *Cypricardella bellistriata;* 18, *Grammysia bisulcata.*

From Paleontology of New York, and Geological Survey of Canada.

Plate 17, Page 708

Fig. 1, *Chonetes setigerus;* 2, *Productella hirsuta* (Upper Devonian); 3, *Tropidoleptus carinatus;* 4 and 5, *Eatonia medialis;* 6 and 7, *Camarotœchia ventricosa;* 8 and 9, *Gypidula coeymansensis;* 10, *Meristella lævis;* 11, *Atrypa reticularis;* 12, *A. spinosa;* 13, *Spirifer pennatus* (*mucronatus*); 14, *Spirifer medialis;* 15, interior and exterior of ventral valve of *Spirifer arenosus;* 16, *Ambocœlia umbonata*, $\times 2$; 17, *Athyris spiriferoides;* 18, *Rensselæria ovoides.*

From Paleontology of New York.

Plate 18, Page 709

Fig. 1, *Oxyclymenia undulata* (Europe); 2, *Aphyllites vanuxemi*, $\times \frac{1}{3}$; 3, *Prolecanites lunulicosta* (Europe), $\times \frac{1}{2}$; 4, *Tornoceras simplex* (Europe); 5, *Brancoceras sulcatum* (Europe); 6, *Manticoceras oxy*, $\times \frac{1}{6}$; 7, *Odontocephalus selenurus*, $\times \frac{1}{4}$; 8 and 9, rolled-up *Cryphæus punctatus*, and same distended (Europe); 10, *Phacops bufo;* 11, *Dipleura dekayi*, $\times \frac{1}{2}$; 12, *Terataspis grandis*, $\times \frac{1}{12}$.

Figs. 1–5, 9, 11 from Gürich's *Leitfossilien;* Fig. 8 after Richter; Figs. 6, 7, 10, 12 from Paleontology of New York.

Plate 20, Page 735

Figs. 1 and 2, *Endothyra baileyi*, $\times 9$; 3, *Axinura canadensis*, $\times \frac{1}{2}$; 4, *Brancoceras ixion*, $\times \frac{1}{2}$; 5, *Melonechinus multiporus*, $\times \frac{1}{3}$; 6, *Pentremites conoideus;* 7, *P. elongatus;* 8, *Agassizocrinus dactyliformis*, $\times \frac{2}{3}$; 9, *Platycrinus symmetricus;* 10, *Batocrinus pyriformis*, $\times \frac{2}{3}$; 11, *Agaricocrinus bullatus;* 12, *Forbesiocrinus wortheni*, $\times \frac{2}{3}$; 13, *Onychocrinus ramulosus*, $\times \frac{2}{3}$; 14, *Cyathocrinus multibrachiatus.*

In the main after the Indiana State Survey.

Plate 22, Page 752

Fig. 1, *Stenodictya lobata;* 2, *Eubleptus danielsi,* × 1½; 3, *Eucœnus ovalis;* 4, *Aphthoroblattina johnsoni,* × ⅓; 5, *Eophrynus prestwichii,* × 1½.

Figs. 1–4 after Handlirsch.

Plate 23, Page 756

Fig. 1, *Triticites secalicus,* × 2; 2, same cut through center, × 8; 3, *Chonetes mesolobus;* 4, *C. verneuilianus,* × 2; 5–7, dorsal and ventral valves, and dorsal interior of *Productus nebraskaensis;* 8 and 9, *P. punctatus,* × ⅔; 10, *P. semireticulatus;* 11, *P. cora,* × ½; 12, *Spirifer cameratus,* × ⅔; 13, *Ambocœlia planoconvexa,* × 2; 14, *Composita subtilita,* × ⅔; 15, *Hustedia mormoni;* 16, *Dielasma bovidens;* 17, *Pseudomonotis hawni,* × ½; 18, *Myalina subquadrata,* × ½; 19, *Allorisma subquadratum,* × ½; 20, *Schizodus harii;* 21, *Leda bellistriata,* × 3; 22, *Euphemus carbonarius,* × 1½; 23, *Soleniscus fusiformis;* 24, *Worthenia tabulata;* 25, *Phillipsia major.*

Figure 433, Page 757

Figs. *A* and *B*, *Solenocheilus kentuckiense,* × ½; *C*, *Domatoceras militarium,* × ½; *D* and *F*, *Glyphioceras incisum,* × 2; *E* and *G*, *Waagenoceras cumminsi,* × ⅘.

From the Texas State Survey.

Plate 24, Page 765

Fig. 1, *Alethopteris grandifolia;* 2, *Neuropteris fasciculata;* 3, *N. capitata;* 4, *Pseudopecopteris mazonana;* 5, tree fern, *Megaphyton,* restored by Kidston; 6, *Sphenopteris mixta;* 7, *Archæopteris stricta;* 8, *Aneimites fertilis,* × 2; 9, same with a young seed, × 4; 10, same, with one of the seeds restored, × 3.

Figs. 1–7 from the Illinois and Ohio State Surveys; Figs. 8–10 after David White.

Plate 25, Page 767.

Fig. 1, restoration of the tree *Lepidodendron,* about × 1/100; 2, leaf of the spore-bearing cone, about × ⅓, those of the branches are very similar but longer; 3, outer surface of tree, showing nature of leaf bases, about × ½ (*L. obovatum*); 4, spore-bearing cone (*Lepidostrobus*), with and without leaves, sectioned to show spores and spore-developing cases (sporangia); 5, bunch of four microspores; 6, macrospore; 7, two species of the tree *Sigillaria,* restored, about × 1/30; 8, section through trunk, showing relative thicknesses of outer leaf-bearing layer, two zones of cork-like bark, comparatively thin internal cylinder of wood, and medial pith; 9, roots of these trees (*Stigmaria ficoides*), with rootlets and scars of their attachment.

Figs. 1–6 after Steinmann; Figs. 7 and 8 after Zittel.

Plate 26, Page 773

Fig. 1, Calamite trees restored, the one on the left bearing a spore case, about × 1/100; 2, basal end of a Calamite; 3, Cordaite tree restored (*Dorycordaites*), about × 1/100, also showing nature of catkin-like flowers; 4, different type of *Cordaites,* about × 1/40; 5, *Trigonocarpon ornatum,* a fruit or seed of a Cordaite; 6, *Rhabdocarpus apiculatus,* seed of a Cordaite; 7, branchlet of the living maiden-hair tree (*Ginkgo biloba*), showing leaves, male flowers, and on the right the mature seed.

Figs. 1 and 2 after Zittel; Fig. 3 after Grand'Eury, from D. H. Scott; Fig. 4 after Dawson, from Le Conte; Figs. 5 and 6 after the Ohio State Survey; Fig. 7 after Steinmann.

PLATE 27, PAGE 799

Fig. 1, *Necturus maculatus* of the Ohio and Mississippi rivers; 2 and 3, *Siren lacertina*, a small salamander, note the three pairs of gills and the absence of hind legs; 4, *Amphiuma tridactyla*, with both gills and lungs; 5, *Trematops milleri*, a stegocephalian, 3 feet long, from Texas; 6, *Cacops aspidephorus*, a stegocephalian, 20 inches long, from Texas.

Figs. 1 and 4 from Parker and Haswell; Figs. 2 and 3 after Lankester, British Museum Guide Book; Figs. 5 and 6 after Williston.

PLATE 28, PAGE 805

Cotylosaurs:

Fig. 1, *Diasparactus zenos*, about 7 feet long, from New Mexico; 2, *Limnoscelis paludis*, about the same length and from the same state.

Pelycosaurs:

Fig. 3, *Varanosaurus brevirostris*, an agile form, nearly 4 feet long, from Texas; 4, *Casea broilii*, of about the same length and from the same state; 5, *Ophiacodon mirus*, about 7 feet long, from New Mexico; 6, *Dimetrodon*, about 8 feet long, from Texas.

All after Williston.

PLATE 30, PAGE 829

Fig. 1, *Pseudomonotis subcircularis*, $\times \frac{1}{2}$; 2, *Daonella dubia*, $\times \frac{1}{2}$; 3, *Atractites burckhardti*, $\times \frac{1}{3}$; 4 and 5, *Anolcites meeki*, $\times \frac{1}{2}$; 6 and 7, *Tropites subbullatus*, $\times \frac{1}{2}$; 8–10, *Joannites nevadanus*, $\times \frac{1}{2}$; 11 and 12, *Meekoceras gracilitatis*, $\times \frac{3}{4}$; 13 and 14, *Gymnotoceras russelli*, $\times \frac{3}{4}$; 15, *Tropigastrites rothpletzi;* 16, *Sageceras gabbi*, $\times \frac{1}{2}$.

After J. P. Smith, from the U. S. Geological Survey.

PLATE 31, PAGE 832

Footprints, $\times \frac{1}{12}$, of:

Fig. 1, *Anchisauripus* (*Brontozoum*) *sillimani;* 2, *Sauropus barrattii* (*Anomœpus major*); 3, *Gigandipus caudatus;* 4, *Eubrontes* (*Brontozoum*) *giganteus;* 5, *Otozoum moodii.*

Restorations, $\times \frac{1}{24}$, of carnivorous dinosaurs:

Fig. 6, *Anchisaurus colurus;* 7, *Podokesaurus holyokensis.*

Fig. 8, restoration, $\times \frac{1}{24}$, of the herbivorous ornithopod dinosaur *Sauropus barrattii;* 9, restoration, $\times \frac{1}{24}$, of the aëtosaur *Stegomus.*

All after Lull.

PLATE 32, PAGE 834

Sauropods:

Fig. 1, *Brontosaurus excelsus*, $\times \frac{1}{180}$; 2, *Diplodocus carnegiei*, $\times \frac{1}{180}$; 3, *Pleurocœlus nanus*, $\times \frac{1}{180}$.

Fig. 4, the predentate *Camptosaurus*, $\times \frac{1}{60}$; 5, the armored *Stegosaurus ungulatus*, $\times \frac{1}{60}$; 6, the bird-catching *Ornitholestes hermanni*, $\times \frac{1}{60}$.

All after Lull.

PLATE 33, PAGE 839

Fig. 1, horned dinosaur, *Triceratops prorsus;* 2, head of *T. elatus*, the culminating form of one line of Ceratopsia; 3, head of another culminating species, *Torosaurus gladius;* 4, older, much horned ceratopsian, *Styracosaurus albertensis;* 5, another older form, *Monoclonius flexus;* 6, bipedal predentate, *Trachodon* (*Claosaurus*) *annectens,* 7, the king tyrant carnivore, *Tyrannosaurus rex.*

All after Lull. About $\times \frac{1}{60}$.

Plate 37, Page 903

Fig. 1, *Terebratula harlani*, × ⅔; 2, *Terebratella plicata;* 3, *Ostrea larva;* 4, *O. lugubris;* 5, *Exogyra costata*, × ½; 6, *Inoceramus vanuxemi*, × ½; 7, *Turritella whitei;* 8, *Admetopsis subfusiformis;* 9, *Cancellaria malachitensis;* 10, *Cryptorhytis utahensis;* 11, *Pyropsis bairdi*, × ½; 12, *Aporrhais prolabiata;* 13, *Scaphites nodosus*, × ½; 14, *Baculites compressus*, × 10; 15, fragment of an adult of same species, to show suture line; 16, *Heteroceras stevensoni*, × ½.

After Stanton, Whitfield, and Scott.

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Fig. *A*, *Scaphites hugardianus; B, Ancyloceras matheronianum* (Aptian), × ½; *C, Hamites rotundus* (Gault); *D, Ptychoceras puzosianum* (Neocomian); *E*, part of straight cone of *Baculites gaudini.*

All from Heer.

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